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New Pleistocene mastodon. By E. H. Sellards.

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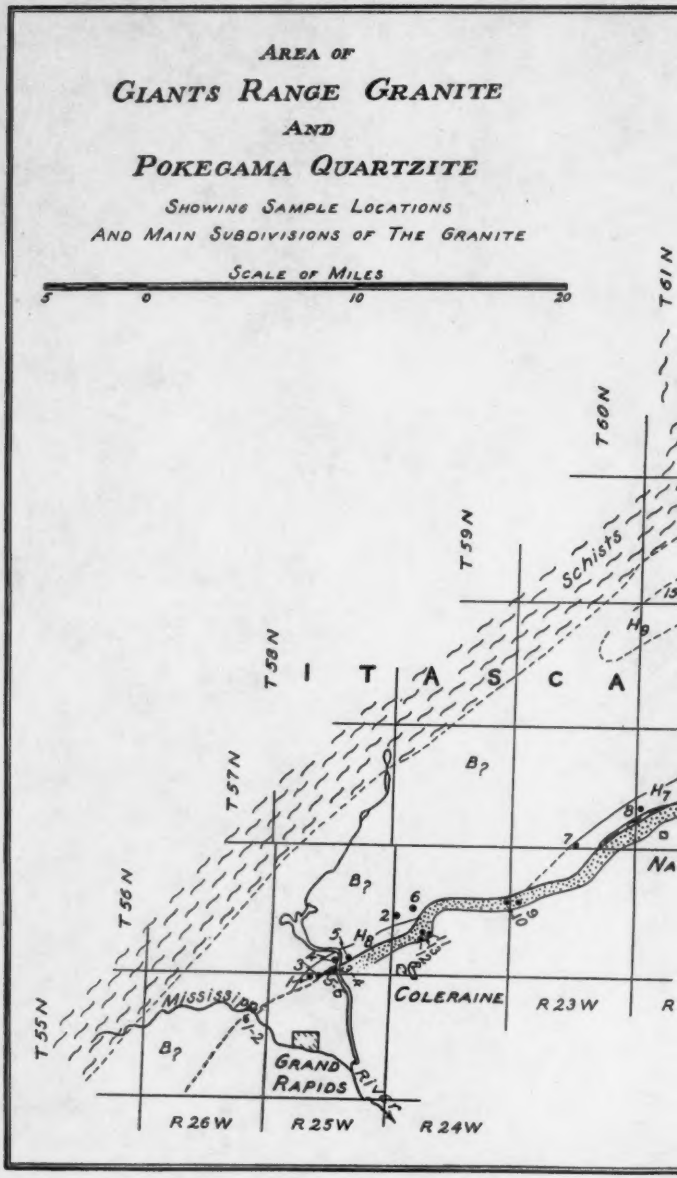
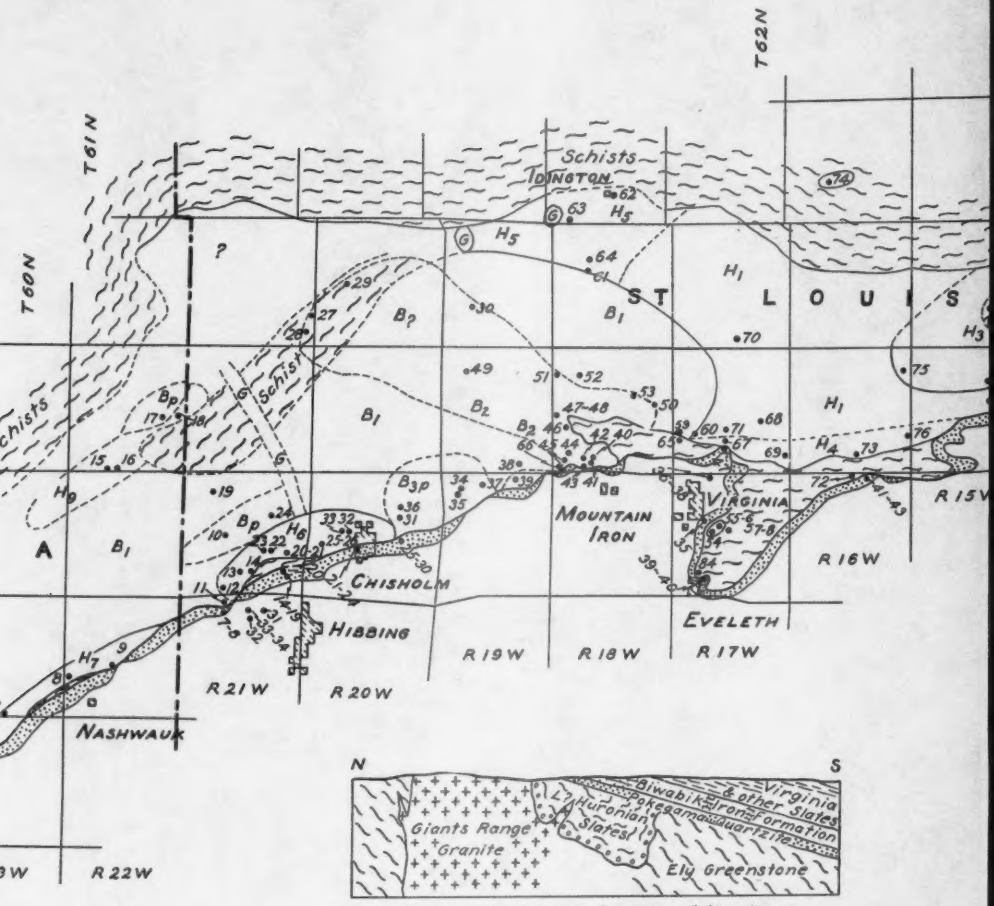
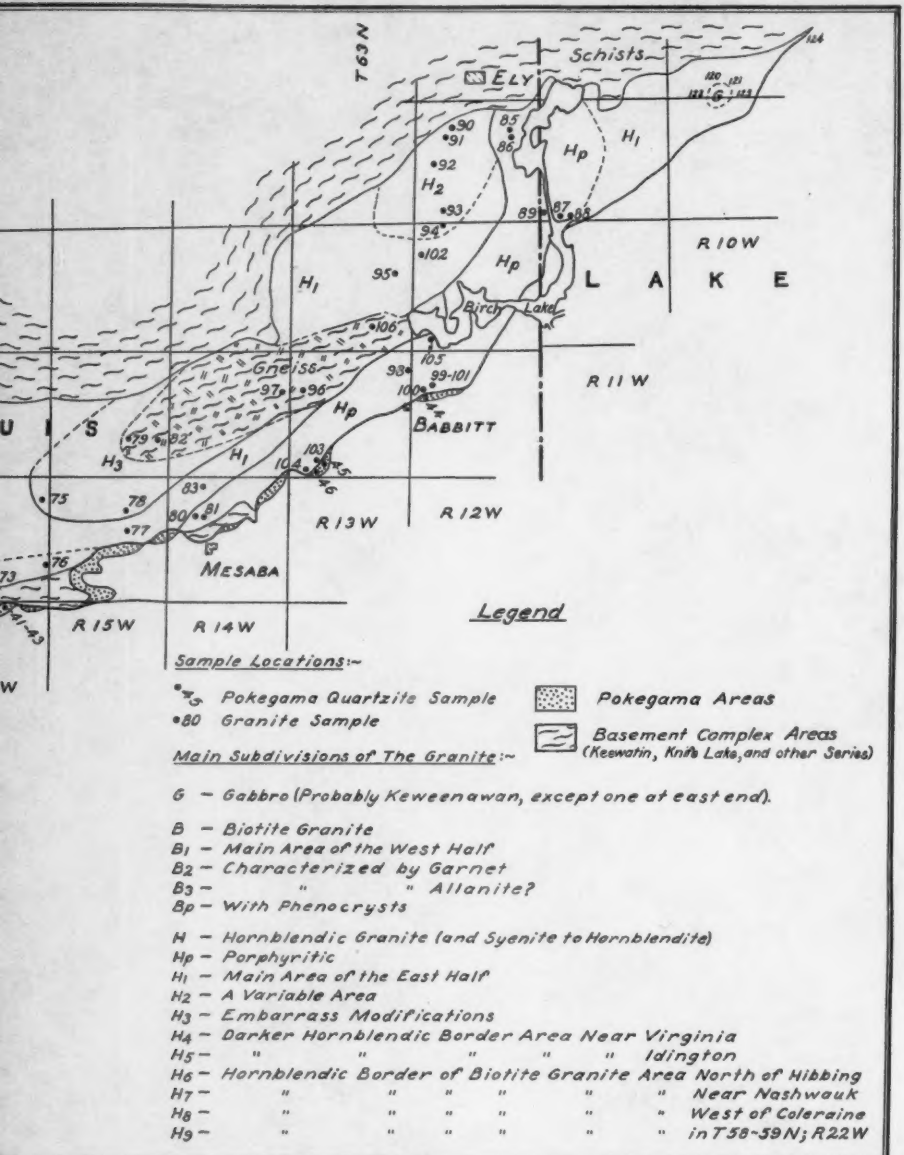

AREA OF
GIANTS RANGE GRANITE
AND
POKEGAMA QUARTZITE
SHOWING SAMPLE LOCATIONS
AND MAIN SUBDIVISIONS OF THE GRANITE
SCALE OF MILES
5
0
10
20
T61N
T60N
T59N
T58N
T57N
T56N
T55N
Schists
ITASCA
Bp
Hg
H7
NA
COLERAINE
R23W
R
Mississippi
GRAND RAPIDS
R26W
R25W
R24W



MAP OF THE GIANTS RANGE GRANITE, POKEGAMA QUARTZITE, AND SURROUNDINGS,

Shows location of samples and areas distinguished by heavy mineral studies.


T 63 N
Schists
ELY
Hp
H1
H2
R 10 W
L A K E
Birch Lake
Gneiss
R 11 W
BABBITT
H3
R 13 W
R 12 W
MESABA
R 15 W
R 14 W
Legend
Sample Locations:-
Pokegama Quartzite Sample
80 Granite Sample
Pokegama Areas
Basement Complex Areas
(Keewatin, Knife Lake, and other Series)
Main Subdivisions of The Granite:-
G - Gabbro (Probably Keweenawan, except one at east end).
B - Biotite Granite
B1 - Main Area of the West Half
B2 - Characterized by Garnet
B3 - " " Allanite?
Bp - With Phenocrysts
H - Hornblendic Granite (and Syenite to Hornblendite)
Hp - Porphyritic
H1 - Main Area of the East Half
H2 - A Variable Area
H3 - Embarrass Modifications
H4 - Darker Hornblendic Border Area Near Virginia
H5 - " " " " " Idington
H6 - Hornblendic Border of Biotite Granite Area North of Hibbing
H7 - " " " " " " Near Nashwauk
H8 - " " " " " " West of Coleraine
H9 - " " " " " " in T58-59N; R22W

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 51, PP. 1429-1538, 4 PLS., 20 FIGS. OCTOBER 1, 1940

STUDIES OF THE LAKE SUPERIOR PRE-CAMBRIAN BY ACCESSORY-MINERAL METHODS

BY S. A. TYLER, R. W. MARSDEN, F. F. GROUT, AND G. A. THIEL

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ABSTRACT

Several hundred samples of pre-Cambrian rocks from the States bordering Lake Superior have been tested for heavy minerals and their ratios. Such ratios are believed to be of little value for correlation of masses of the same age or for distinction of those of different ages.

Early pre-Huronian rocks on the south shore of Lake Superior and pre-Animikie intrusives north of the lake commonly have the "hyacinth" variety of accessory zircon, resembling the "purple" zircon described by Mackie from the pre-Cambrian of Scotland. Late pre-Huronian and Huronian rocks south of Lake Superior carry malacon alone, or more rarely malacon with some hyacinth that may be derived by incorporation of the older rocks. Intrusive rocks north of Lake Superior have not as yet yielded any abundant accessory malacon, and intrusives of the age of those bearing malacon in the southern areas may be rare north of the lake. Keweenawan igneous rocks on both sides of Lake Superior carry zircons that are characteristically euhedral simple crystals, colorless to pale yellow brown. These Keweenawan igneous rocks may, like the Huronian, have at places incorporated older rocks, but very few heavy separates have shown such contamination. The differences in those three types of zircons suggest very important correlations of certain granite masses, the age of which was not clearly settled by field relations.

The dates of exposure of these igneous rocks are reflected in the sediments, showing the varieties of zircons derived from them. The detrital heavy mineral suites in all the Huronian and pre-Animikie sediments studied are so similar in the characters of the zircons and so irregular in the authigenic accessory minerals that individual Huronian formations cannot be distinguished by heavy mineral methods. Such methods, however, distinguish Huronian and older sediments from those of Keweenawan age and correlate certain formations of the Upper Keweenawan where the field observations left some uncertainty. In this respect the Keweenawan sediments resemble the Paleozoic and later sediments which have at places been correlated by heavy mineral work.

Several generalizations as to igneous accessory minerals can be based on the data, especially those on the Keweenawan rocks: (1) The average relative percentages of accessory minerals is different for rocks of different composition even if the rocks are of the same age and appear to be genetically related; (2) The type of dominant zircon in Keweenawan rocks is remarkably constant regardless of rock composition—so long as zircon can be concentrated—and almost regardless of the texture and cooling history of the rock.

The changes in heavy accessory minerals in weathering and sedimentation are striking, and the data in this region do not wholly agree with previous remarks as to which minerals are most rapidly attacked and which least by such processes. More work is needed.

INTRODUCTION AND ACKNOWLEDGMENTS

The Lake Superior region is particularly significant to students of pre-Cambrian geology because it presents one of the most complete successions of pre-Cambrian rocks in the world. The geologic histories of many of the separate districts are known in considerable detail, but it has been difficult to correlate formations from one district to another. Correlations generally have been based on similarity of lithology, continuity and sequence of strata, matching of unconformities, and the relations of intrusion and metamorphism to sedimentary formations, but it is unwise to rely wholly on these methods.

During the past 2 decades it has been shown that certain accessory minerals are useful in correlating Paleozoic and later strata. There has been some application of this method to pre-Cambrian rocks. In 1933 C. K. Leith made brief reference to the possibilities of this method in his presidential address to The Geological Society of America. Previously, Twenhofel and Winchell of the University of Wisconsin and Grout and Thiel of the University of Minnesota had become interested in the application of such studies to the problem of the Lake Superior pre-Cambrian and had requested a grant-in-aid from The Geological Society of America. Grants were received in 1934 and in 1935. The work has also been supported by the University of Minnesota and the University of Wisconsin.

The studies in Wisconsin and northern Michigan were conducted by Marsden and Tyler of the University of Wisconsin, and those in Minnesota were made by Grout and Thiel and a group of assistants; the sections of this report on these two divisions of the area were prepared largely by these two groups separately. The writers wish to express their thanks to F. T. Thwaites, L. M. Scofield, R. R. Shrock, and R. M. Dickey for their many suggestions and criticisms; and to C. A. Lamey for the loan of heavy mineral slides from the Southern Complex of the Marquette district. Credit is due Mr. E. J. Lyons, who studied 19 granite samples from the central Gogebic area and to Mr. B. W. Meek, who studied 41 samples of the Palms quartz slate. In Minnesota field work able assistance was given by George Gibson, S. W. Sundeen, Sam Goldich, and A. E. Sandberg; and in laboratory and office work by Sam Goldich, Gordon Rittenhouse, Robert Grogan, Harlan Bergquist, Ernest Berg, Gilman Berg, R. A. Bowen, Lee Armstrong, Benjamin Alvarado, and Ed Dobrick. Winchell and Twenhofel have assisted with advice, suggestion, and criticism throughout the study. The advice of C. K. Leith during the preparation of the final report is greatly appreciated.

Both groups started work with the broadest ideas of contributing data that might solve geologic problems. It was certain that the study would disclose the heavy mineral content of pre-Cambrian rocks, available for contributions to later sediments. It was hoped that there might be applications to correlation, structure, and paleogeography. Several hundred samples were collected.

After about a year's work a conference showed agreement in the conclusion that one assumption in previous work on igneous rocks was unfounded—namely, that the ratios or relative percentages of the heavy accessory minerals are uniform or constant throughout an igneous rock. The conference also resulted in modifications of laboratory procedures (Winchell, 1935) and methods of reporting results, and all were satisfied that the results of the two groups were comparable. The already published results of tests of accuracy of the methods (Winchell, 1937) are a by-product of the main research.

After this conference the two groups adopted rather different procedures and worked toward different objectives, largely because of differences in the material available. The Minnesota group had available two granite batholiths and a series of Keweenawan igneous rocks, which had contributed to adjacent pre-Cambrian sediments. The first effort was to determine for each batholith the range of ratios or relative percentages of heavy accessory minerals. One batholith is a simple well-defined unit, the other a composite. The differences in the heavy minerals in source rocks and their derived sediments were then studied.

The Wisconsin group studied igneous rocks of accurately determined relative ages. The absence of distinctions in the ratios of heavy accessory minerals induced closer studies of varieties of each mineral. A series of distinctive varieties of zircons was discovered, and the technique was modified so as to concentrate zircons for more detailed studies. This technique has proven very useful.

In the oldest granites the zircons resemble those described by Mackie in his studies of the Archean of Scotland and Canada. The successively later granites have other distinguishable varieties of zircon. These differences could not be seen in the Minnesota rocks, because the Laurentian and Algoman batholiths both have the variety of zircons that dominates in the oldest granites, and there are few if any granites that are late Huronian or Keweenawan. The granitic differentiates of Keweenawan basic intrusives are so stained with hematite that the colors are obscured. A further modification of technique, involving acid treatment before mounting for study, brought all results into accord. They suggest a number of important correlations.

In anticipation of the results of the studies it may help the reader to glance at the general sequence of formations and series, comparing previously published ideas with those based on the present study.

South Shore (Leith, Lund, Leith, 1935)	South Shore (Heavy mineral and field correlation)	North Shore (Heavy mineral and field correlation)
Granite (*Killarney*) Keweenawan series	*Granite* (*Keweenawan*) Keweenawan series	*Granite* (*Keweenawan*) Keweenawan series
	Granite (*Late Huronian*)	
Huronian series	Huronian series	Huronian series (Animikie group)
	Granite (*Pre-Cambrian*) Younger (malacon-bearing)	
Granite (*Laurentian*)	Older (hyacinth-bearing)	*Granite* (*Algoman*) Knife Lake series
		Granite (*Laurentian*)
Keewatin series	Keewatin series	Keewatin series

FIELD WORK

Samples of granites were collected from fresh exposures, by taking from an area of perhaps 100 square feet at arbitrary distances a series of chips about an inch across. Each sample weighed 5 to 6 pounds. Some years ago, four large samples of Giants range granite were taken, 200 to 400 pounds per sample, and tabled on an ore-testing machine to obtain a large batch of heavy accessory minerals. These samples have been studied, and concentrates are still available.

The Giants range batholith is the largest igneous mass sampled in this work, and about 100 samples were taken for detail. Less extensive series of samples were taken from the granite at Saganaga Lake, from granites in central Minnesota, and across Wisconsin and northern Michigan, and from the complex series of Keweenawan igneous masses.

In sampling the pre-Cambrian sediments a different method is required. An attempt was made to collect samples that represented stratigraphic intervals of from 3 to 5 feet. Channel sampling was impracticable at some exposures because of the quartzitic nature of the rock. At such exposures, however, chip samples were taken from all the layers

TABLE 1.—*Correlation of formations in the Lake Superior region*

Modified from Leith, Lund, and Leith (1935)

			Gogebic	Marquette	Felch Mt.	Florence	Mesabi	Vermilion
ALGONKIAN	Keweenawan	Upper	Sandstone, shale, conglomerate					
		Middle	Gabbro and granite	Basic intrusives	Basic intrusives		Duluth gabbro	Duluth gabbro
			Basic and acid flows, some sandstone and conglomerate					
		Lower	Sandstone and conglomerate					
			~~Unconformity~~					
			Granite	Granite	Granite	Granite		
	Huronian	Upper	Tyler Slates	Upper Michigamme slate Bijiki iron formation Lower Michigamme slate Clarksburg volcanics Greenwood iron formation Goodrich quartzite		Upper Michigamme slate Florence iron formation Lower Michigamme slate Quinnesec greenstone Breakwater quartzite	Virginia Slates	Rove Slates
				~~Unconformity~~			~~?~~	~~?~~
		Middle	Basic intrusives and extrusives Ironwood iron formation Palms quartzite	Negaunee iron formation Siamo slate Ajibik quartzite	Vulcan iron formation Felch schist	Little Commonwealth i. f. Spread Eagle greenstones	Biwabik iron formation Pokegama quartzite	Gunflint iron formation KAKABEKA
				~~Unconformity~~				
		Lower	Bad River dolomite Sunday quartzite	Wewe slate Kona dolomite Mesnard quartzite	Randville dolomite Sturgeon quartzite	Saunders formation Keyes Lake quartzite		
				~~Unconformity~~				
	Algoman		*	*	*	*	Giants Range granite	Vermilion granite
	Knife Lake						Knife Lake slates	Knife Lake slates
							~~Unconformity~~	
ARCHEAN	Laurentian		Granite	Granite	Granite	Granite		Saganoga granite
	Keewatin		Greenstone and green schists	Kitchi schist and Mona schist			Greenstone, schist & porphyries	Soudan iron formation Ely greenstone

* Late pre-Huronian granite may occur in these areas.

in a given section. The outcrops of slaty facies are commonly weathered near the surface, and such outcrops were cleaned before sampling. In the Mesabi district, it was possible to obtain also some drill cores of unweathered sediments at various depths. The sediments associated with Keweenawan igneous rocks are not so firmly cemented, and channels were cut for most samples.

The selection of samples upon which the correlation of the various batholithic invasions is to be based is of paramount importance. The relative age of the samples should be known beyond doubt if they are to be used as standards. Such samples are here defined as type samples. The question of what constitutes clear evidence for selecting type samples may arise. It is evident that granite pebbles in a conglomerate were derived from a granite older than the sediments; likewise, the granite upon which the conglomerate rests is older than the sedimentary series. However, unless the granite can be identified by some petrographic peculiarity or by some other method equally good, a sample taken from a separate outcrop even a short distance from that contact is of unknown age, for its relation to the sediments is unknown. After the heavy accessory suite has been established from the type outcrops, correlation with outcrops of uncertain age may be undertaken. In studying an igneous-sedimentary sequence as complex as that of the pre-Cambrian, the selection of type samples is difficult; in some cases it is impossible to find outcrops where relative ages are sufficiently clear.

DATA FROM THE SOUTH SHORE OF LAKE SUPERIOR

BY S. A. TYLER AND R. W. MARSDEN

PRE-HURONIAN COMPLEX

GENERAL STATEMENT

The dominantly igneous sequence unconformably beneath the Algonkian series in the Lake Superior region (Table 1) is designated Archean and is divided into two major groups—the Laurentian and the Keewatin. The term Archean has been applied, in general, to areas of igneous rocks dominantly pre-Algonkian in age but it may also include younger igneous rocks. Wherever intrusive rocks cut the Archean the sequence becomes complicated and difficult to interpret. Because of this complexity it has been necessary to use the greatest care in selecting type samples.

HEAVY ACCESSORY MINERALS

General statement.—The heavy accessory minerals in the pre-Huronian igneous rocks examined are apatite, ilmenite, leucoxene, rutile, sphene,

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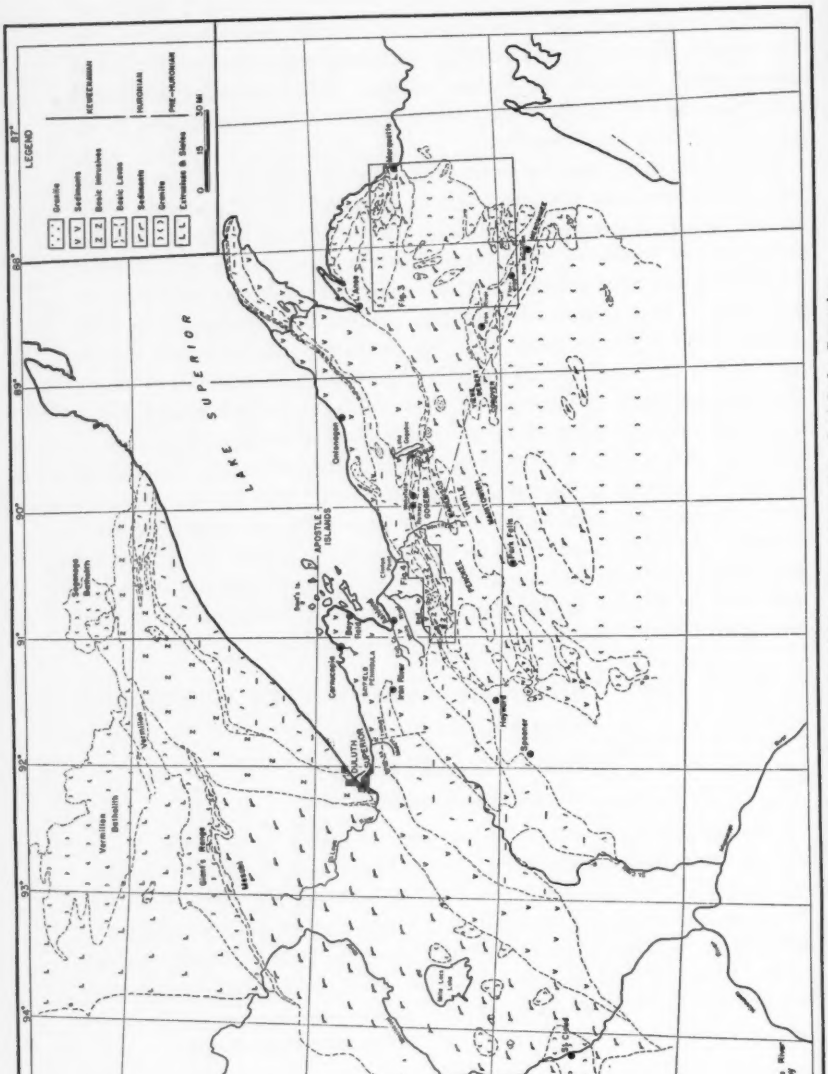
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Giant's Range
Hayward
Spooner
Black Falls
Chequamegon Bay
Bayfield Peninsula
Marquette
Menominee
Iron River
Crystal Falls
Florence
Crystal Lake
Mellen
Ashland
Bessemer
Gogebic
Penokee
Gile Flowage
Michigamme Reservoir
Lake Gogebic
Lake Michigamme
Lake Gile
Lake Vieux Desert
Lake Antoine
Lake Mary
Lake Ottawa
Lake Fanny Hooe
Lake Ottawa
Lake Ottawa
Lake Ottawa

TABLE 2.—*Relative percentages of heavy and accessory minerals in hyacinth-bearing igneous rocks*

Pre-Huronian of the south shore of Lake Superior

	Heavy minerals						Accessory minerals						
	Sample no.	Hornblende	Biotite	Chlorite	Epidote	Accessory minerals	Zircon	Apatite	Garnet	Sphene	Rutile	Ilmenite	Leucoxene
Granite, Northern Complex, Marquette district—west end	2	33	40	x	23	4	x	31	....	....	....	68	1
	6	11	36	....	36	17	9	46	....	45	....	....	....
	12	x	73	5	1	21	12	67	....	....	....	8	13
	16	....	73	3	18	6	17	75	....	....	....	8	....
	22	x	22	8	55	15	16	77	....	....	....	7	x
	24	x	42	13	9	36	17	55	....	....	....	9	19
	34a	66	x	9	....	25	4	31	22	....	....	27	16
	40	x	16	x	48	36	7	73	x	....	....	9	11
	44	10	57	x	25	8	1	27	....	59	....	13	....
	45	....	2	2	....	96	4	52	....	x	40	2	2
	148	....	12	....	42	46	27	47	....	....	....	23	3
	159	....	70	14	x	16	5	55	....	....	....	31	9
	160	x	15	15	x	70	x	50	....	....	47	3	....
	162	....	23	22	x	55	3	46	....	....	1	31	19
Granite, Northern Complex, Marquette district—east end	137	69	....	x	14	17	8	46	....	11	1	28	6
	138	34	....	7	28	31	5	35	....	45	....	14	1
	139	1	....	x	81	18	8	42	....	x	....	41	9
	140	43	....	1	41	15	3	39	....	....	....	47	11
	141	....	....	3	21	76	7	31	....	x	....	44	18
	142	4	....	....	61	35	10	33	....	30	....	22	5
Syenite, Northern Complex, Marquette district	76	80	13	x	....	7	x	92	....	3	....	3	2
	143	70	7	x	....	23	....	69	....	8	....	15	8
Granite gneiss, Big Bay, Michigan	133	84	....	....	8	8	x	50	....	42	....	5	3
	134	96	....	....	x	4	....	x	....	99	....	1	....
	135	90	....	....	5	5	....	2	....	98	....	....	....
Granite gneiss, Palmer, Michigan	95a	83	9	....	x	8	x	10	....	78	....	5	7
	118	....	....	63	....	37	x	6	....	....	....	90	4
Granite, Presque Isle, Gogebic range	183	x	36	x	x	64	19	63	....	....	....	11	7
	184	4	10	x	14	72	2	27	2	....	....	54	15
	185	2	22	3	32	41	11	16	....	....	....	52	21
	186	1	x	85	....	14	9	78	2	....	....	x	11
Granite south of Penokee Gap	260	....	....	x	96	4	5	94	....	....	....	1	x
	261	4	84	....	x	12	7	83	....	....	....	5	5
	262	....	43	....	17	40	11	87	....	....	....	1	1
	266	79	10	....	2	9	3	39	....	17	....	40	1
	267	4	71	....	14	11	23	28	....	34	....	14	1
	268	....	91	1	1	7	22	78	....	x	....	....	....
	270a	....	94	....	1	5	10	79	....	x	....	11	x
	271	83	12	....	1	4	x	17	....	x	....	83	....
	271a	27	60	....	9	4	12	80	....	5	....	3	....

x=less than 1 per cent.

FIGURE 1.—*Index map of the area near west end of Lake Superior*

and two varieties of zircon—hyacinth and malacon. The hyacinth occurs in the older granites to the almost entire exclusion of malacon, whereas the malacon is found in younger granites some of which may carry xeno-

TABLE 3.—*Relative percentages of heavy and accessory minerals in malacon bearing igneous rocks*

Pre-Huronian and Huronian, of the south shore of Lake Superior

		Heavy minerals					Accessory minerals							
	Sample no.	Hornblende	Biotite	Chlorite	Epidote	Accessory minerals	Zircon	Apatite	Tourmaline	Garnet	Sphene	Rutile	Ilmenite	Leucoxene
Granite gneiss south of Palmer, Michigan	95	....	78	1	9	12	15	66	....	....	....	....	19	x
	116	15	62	6	8	9	10	45	....	....	36	....	9	x
	116a	....	52	23	15	10	9	85	....	....	4	....	2	x
	116b	....	38	39	4	19	x	46	....	....	....	....	47	7
	117a	....	40	7	3	50	8	63	....	....	....	....	13	16
	118a	x	1	2	....	97	2	3	....	....	....	x	95	x
	119a	....	75	1	14	10	28	68	....	....	....	....	4	....
Red granite south of Palmer, Michigan	85	....	81	....	....	19	30	65	....	....	....	....	2	3
	87	....	52	....	....	48	20	68	....	....	....	....	9	3
	89	....	x	1	....	99	15	36	....	....	....	35	10	4
	91	....	85	1	x	14	20	79	....	....	....	....	1	....
	92	....	76	11	3	10	6	90	....	....	....	....	2	2
	93	....	....	....	1	99	13	50	....	....	....	20	17	x
	94	....	19	3	9	69	36	15	....	....	....	2	26	21
Granite south of Beacon, Michigan	50	....	91	3	....	6	26	74	....	....	....	....	....	....
	51	....	24	32	30	14	44	46	x	....	....	....	10	x
	52	97	x	x	....	3	7	72	....	....	....	....	21	....
	53a	11	84	x	2	3	53	22	....	....	....	....	22	3
	54	....	57	35	x	8	82	8	....	....	....	....	8	2
	55	10	89	....	....	1	15	31	....	....	41	....	13	....
	56	x	55	4	5	36	6	42	....	....	....	....	52	....
Granite pebbles, Lake Pelissier	99	....	....	....	....	100	7	34	....	....	....	x	42	17
	100	1	....	....	....	99	2	8	....	....	....	....	78	12
	103	1	....	2	....	97	12	13	....	....	....	1	50	24
Granite, Lake Pelissier	96	....	....	23	....	77	10	60	....	....	....	....	4	26
	97	....	....	....	....	100	2	13	....	....	....	....	77	8
	98	....	....	....	....	100	7	9	....	....	....	....	34	50
	101	....	1	....	....	99	6	35	....	....	....	2	45	12
Granite gneiss, Big Bay, Michigan	133a	x	....	20	55	25	3	23	....	....	15	....	46	13
	135a	....	85	....	11	4	2	8	....	....	x	....	87	3
Huronian granite dikes, Felch district	171	40	50	1	2	7	1	34	12	19	....	....	30	4
	176	x	1	....	....	99	x	x	....	....	....	....	98	2
	178	....	....	81	....	19	x	36	....	....	....	....	62	2
Granite, Presque Isle area, Gogebic range	179	64	1	28	6	1	61	....	....	....	27	....	10	2
	180	....	54	....	30	16	43	....	....	....	....	....	27	30
	182	x	31	....	1	68	11	9	....	1	28	x	36	5
	187	....	90	x	1	9	11	10	....	68	....	....	6	5

x less than 1 per cent.

crysts of hyacinth. The relative percentages of heavy and accessory minerals in the hyacinth-bearing granite are given in Table 2, and those of the malacon-bearing granites in Table 3.

Hyacinth.—The color of the zircons ranges from a very faint pinkish tint to a deep brownish purple, purple, and pink. The distinctly colored ones are slightly pleochroic from dark to light purple and are known as hyacinth. Prismatic grains with several pyramidal faces are common; in some grains this gives the impression of rounding. Grains with definitely rounded crystal angles are common, and some are so well rounded that they resemble detrital grains although they occur in granite. Some grains have a ditetragonal prism, whereas others have only the normal prism associated with a steep pyramid. The grains commonly show faint zoning and contain a few crystalline inclusions. The surfaces of the zircons may be smooth or may show slight irregularities and striations. The fractures, evident in some grains, may be related to the crushing operation or may be primary.

The indices of refraction were determined at 26° C. with sodium light using a series of index liquids consisting of methylene iodide, sulphur, and yellow phosphorus. The index of refraction of the liquid was determined by the minimum deviation method using a hollow prism. $N_o = 1.900 - 1.905$, $N_e = 1.940 - 1.945$, $N_e - N_o = .04$. Probable accuracy of index $0.005\pm$.

The hyacinths from this region are very similar to the "purple zircons" from the rocks of Scotland. Mackie (1925, p. 200-213) described these in the Lewisian gneiss and Moine schist and proved their distribution from that source to the sedimentary rocks of the British Isles. He also reports this variety of zircon in some granites and gneisses of Canada.

Malacon.—This variety of zircon is characterized by abnormally weak birefringence, dull luster, and cloudy altered appearance. The grains usually have a rounded prismatic to spherical outline; a few are euhedral elongated prisms with steep pyramids. The dimensional ratios observed range from 6 : 1 to about 1 : 1. The zircons are colorless to pale dirty yellow, and many contain abundant dustlike inclusions suggesting alteration. A few are zoned parallel to the exterior form, and many grains have etched and striated surfaces.

Zircons of this type show birefringence of the first order gray and yellow, and occasional large grains show the first order red. In some the birefringence is variable. Grains of normal zircon comparable in size would have birefringence in the second or third orders. The index ranges from 1.795 to 1.850. Shadowy extinction and a double Becke line makes it difficult to obtain accurate results. It is evident, however, that this variety has a wide range in index of refraction and that the upper limit is below the lower index of hyacinth. This type is thought to be the variety "malacon" or more specifically the "c" zircon of Steva-

novic (1903, p. 247-254). According to Chudoba and Stackelberg (1936, p. 230-246), when "c" zircon is heated to 1450° C. for 6 hours it changes to normal "b" zircon with normal high gravity, refringence, and birefringence. The writers tried this test on their type of malacon, but a temperature of only 1300° C. was reached with the equipment available. After 5 hours at 1300° C. the malacon changed from transparent to translucent with a marked increase in birefringence. Therefore, if a temperature of 1450° C. had been attained for the proper length of time, the zircon probably would have changed completely to normal zircon.

The altered appearance of this type of zircon suggested that the grains might be hyacinth decolorized by exposure to heat or a radioactive element. To check this possibility, hyacinth grains were decolorized by heating; however, they retained their original bright vitreous luster and normal birefringence. In no way did they resemble malacon. An attempt to color the malacon by exposure to radium chloride, similar to the method described by Strutt (1914, p. 405-407), proved unsuccessful. There was no noticeable change in color. Hyacinth was also exposed to 4 milligrams of radium chloride for 120 hours with no change in properties.

Malacon may simply be a hydrated form of zircon, resulting from weathering of ordinary zircon. This does not seem to be true, however, for malacon occurs in dikes cutting metamorphosed sediments, whereas the metamorphosed sediment adjacent to the dike contains only zircon of normal birefringence. The alteration would have to be selective, affecting the zircon in the dike and not that in the metamorphosed sediment. This suggests that the zircon in the dike and sediment originally differed in chemical composition. If this is true, the malacon is probably related to the igneous history or chemical composition of the intrusive.

A few hyacinths occur within grains of malacon. The knife-edge contact between the two types of zircon could be the result only of a marked change in the composition of the zircon. The converse is not true, for in none of the hundreds of slides examined have hyacinths included malacon grains. The hyacinths included within malacon are thought to be xenocrysts from earlier rocks which have become incorporated in the granite containing malacon. If this is true, the association of the two types of zircon should be particularly common in localities where a later granite containing malacon intimately intrudes an older granite containing hyacinth; this appears to be so in the field occurrences. Zircon xenocrysts apparently are not rare, for Mackie (1925, p. 211-212) refers to them in Scotland.

Accessory minerals of secondary importance.—The following heavy accessory minerals occur in the pre-Huronian complex but seem to be of secondary importance for correlation purposes.

APATITE: Occurs in all the samples studied, and the differences of varietal characteristics of this mineral within a given sample may be as great as the variations within a single igneous body or even in rocks of different ages. It is found as clear, colorless grains, usually prismatic with rounded terminations, and as irregular fragments produced by crushing. The grains may contain colorless or opaque, irregular, globular, and crystalline inclusions, which give some of them a cloudy appearance. An occasional cored apatite is found.

GARNET: Irregular fragments ranging from light pink to colorless are in relatively few samples.

ILMENITE: Common. Irregular grains more or less altered to leucoxene are present in most of the samples. They range from a trace to 96 per cent of the accessory minerals. It has been impossible to distinguish any difference in the ilmenite, which might be used for correlation.

LEUCOXENE: Occurs as granular opaque grains, which are waxy yellow white in reflected light. It is a common constituent of the rocks studied and, since it is an alteration product of ilmenite and sphene, has little value for correlation.

MAGNETITE: Common. Occurs as irregular grains or as octahedral crystals. The wide distribution and lack of difference in its varietal characteristics prevent its use for correlation.

MARTITE: May be distinguished from the magnetite by decreasing the field strength of the electromagnet and from ilmenite by the crystal form.

RUTILE: The irregular foxy-red to brown grains and prismatic crystals are thought to be of secondary origin. It is locally very abundant.

SPHENE: Occurs in many samples in quantities ranging from flood to a trace. Irregular fragments which are in part, at least, a result of crushing are common, and flattened monoclinic crystals are rare. The crystalline variety is pale tan, whereas the irregular fragments range from almost colorless to yellow and brown; some of the deeper brown grains are pleochroic from brown to yellow brown. Most of the grains are clear, but some contain crystalline inclusions. The percentage of sphene in an igneous body is variable, but there is commonly a marked increase near an intrusive contact.

KEEWATIN

The Keewatin—oldest known series in the region—consists of greenstones, basic and acidic schists, tuffs, and agglomerates. This series is cut by the Laurentian and Huronian granites and by the Keweenawan intrusive rocks. Nine samples of greenstone schist were studied, and the following heavy accessory minerals were noted: apatite, ilmenite, leucoxene, pyrite, and rutile, with a few grains of hyacinth in some samples. The classification of zircon as the hyacinth variety is tentative because of its extreme rarity in the Keewatin greenstone.

GRANITE OF NORTHERN MICHIGAN AND WISCONSIN

General statement.—The granitoid gneiss, granite, and syenite unconformably below the Huronian in this area were designated Laurentian by Van Hise and Leith (1911). Because of the absence of the Knife Lake series in northern Michigan and Wisconsin the relation of the pre-Huronian granite to the Knife Lake is not known. However, the pre-Huronian granite of the Wisconsin-Michigan region has been correlated

by Van Hise and Leith with the Saganaga granite of northeastern Minnesota, which is considered post-Keewatin and pre-Knife Lake. More recently some of the granites called Laurentian on the South Shore, such as the Presque Isle and Republic granites, have been found to be post-upper Huronian.

Pre-Huronian igneous rocks include a major portion of the Northern Complex of the Marquette range and part of the Southern Complex. They are found in the Felch trough and on the Gogebic range in the Presque Isle area, the central granite area, and the western area. The pre-Huronian type of accessory mineral suite was established in these areas by studying samples from localities where the granite is unconformable beneath the Huronian.

By defining the conditions under which type samples should be taken, most of these granites are eliminated from consideration as types. The following samples were taken from localities where the relations are so clear as to eliminate doubt of the pre-Huronian age of the granite: granite pebbles from the conglomerate at Mud Lake (sec. 29, T. 48 N., R. 25 W.) along the contact between the granite and the Ajibik quartzite north of Lake Michigamme and north of Clowry, Michigan; granite pebbles from basal Sturgeon conglomerate in the Sturgeon River tongue (NW¼ NE¼ sec. 7, T. 42 N., R. 28 W.) (Fig. 3); the granite and conglomerate on the Gogebic range south of the Palms mine (Fig. 2); and the Newport and Aurora mines. These localities are described in the original monographs.

Central granite area of the Gogebic range.—South of the Huronian formations in the vicinity of Ironwood is a large area of hornblende and biotite granite, termed central granite (Fig. 2) by Irving and Van Hise (1892, p. 111-116). It was described as massive granite, syenite, and granite gneiss. This granite, called Laurentian because of its unconformable relations with the Huronian, closely resembles the granite of the western and eastern areas.

More recently L. M. Scofield (personal communication) has discovered two granites in the area—an older which is unconformable below the Palms quartz slate, and a younger which is intrusive into the older. The intrusive relations are well illustrated south of the Newport mine, in cross-cuts in the mine, on Norrie Hill south of Ironwood, and near the southeast corner of the SW¼ of sec. 17, T. 45 N., R. 3 E., about 5 miles south of Hurley, Wisconsin.

The older, massive to gneissic medium-grained gray to pink hornblende granite is well exposed south of the Palms mine where it lies directly below the basal conglomerate of the Palms formation. The conglom-

erate contains chert, quartz, jasper, and granite pebbles. The granite is also exposed in a ventilation drift on the 27th level of the Newport mine and south of the Aurora mine. The granite here, as at the Palms

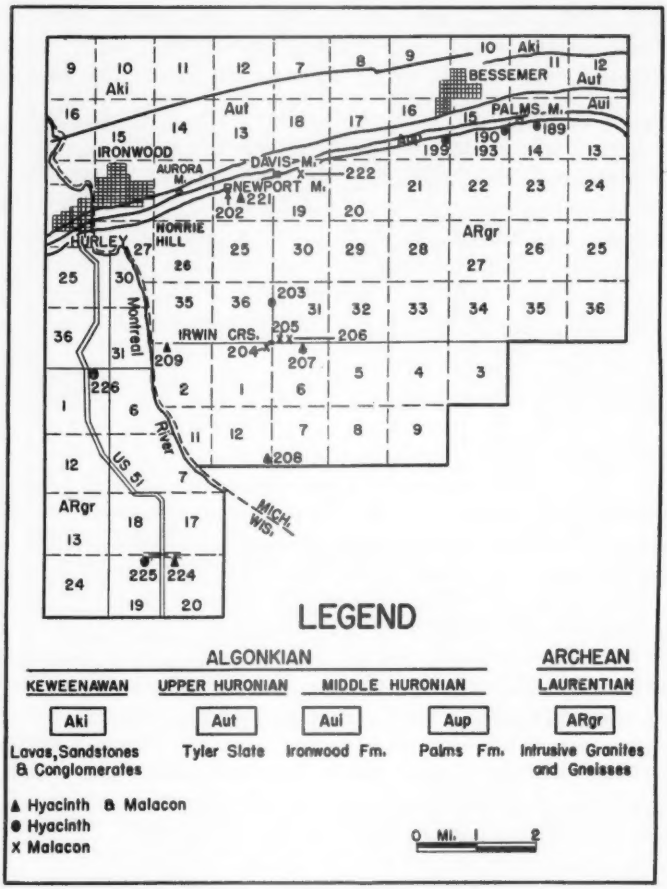

FIGURE 2.—*Map of a portion of the Penokee-Gogebic district*

mine, is directly below the basal conglomerate of the Palms quartz slate.

All samples of the older granite are characterized by hyacinth which is similar in all respects to that found in the pre-Huronian granite of the Marquette region.

The younger granite—a massive medium-grained gray to pink porphyritic biotite granite—was included in the Archean by Irving, Van Hise, Leith, and others and was not recognized as a distinct intrusive.

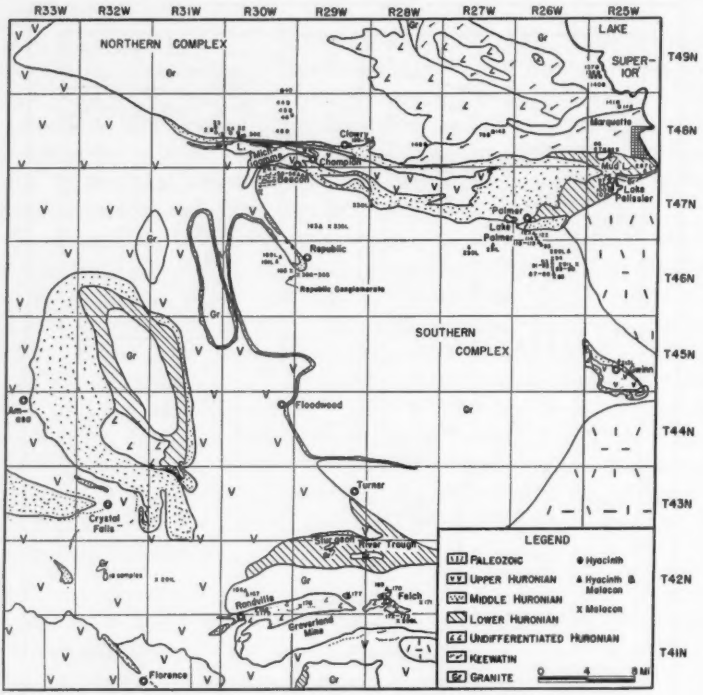

FIGURE 3.—*Map of Marquette and associated areas of Michigan*

All samples of the younger granite examined contain either malacon or a mixture of hyacinth and malacon. The presence and abundance of malacon distinguish the younger from the older granite. The malacon-bearing granite is in contact with the Palms formation near the Davis mine and southwest of the Newport mine. Pebbles of this granite occur in the basal Palms conglomerate at the Aurora mine, proving that some of the malacon-bearing granite is pre-middle Huronian.

Penokee Gap area.—The granite south of Penokee Gap, near Mellen, Wisconsin, was called Laurentian by Irving (1880, p. 92-96), and his classification has been adopted by later workers in the area. The igneous

rocks consist of granites, greenstones, and gneisses. The gneisses appear to be the oldest and are intruded by two granites. This area conforms to the general sequence in the other regions studied, for the oldest rock—the granite gneiss—is characterized by hyacinth. The intermediate granite contains malacon, and the youngest a type of zircon which is characteristic of the Keweenawan igneous rocks. The reader is referred to the later description of zircons of the middle Keweenawan igneous rocks.

Presque Isle area.—The Presque Isle area is included in the region referred to by Irving and Van Hise (1892, p. 122) as "the Eastern Laurentian" area of the Gogebic range. The granite was considered to be Laurentian and to lie unconformably beneath the Huronian series. Later, Allen and Barrett (1914, p. 50-54) regarded the granite as post-Middle Huronian since it was believed to be unconformably overlain by the Copps formation. Leith, Lund, and Leith (1935, p. 13) state:

> "Subsequent work has shown that granite of two ages is present in this area, much the larger part being Laurentian or pre-Huronian, and a comparatively small part (the Presque Isle granite) being intrusive into the Middle Huronian Palms and Ironwood formations and the Upper Huronian Tyler slate. The granite pebbles in the conglomerate (base of the Copps) member of the Tyler are now regarded as having come from the earlier granite."

As a result of this work the younger granite in the Presque Isle area was considered Keweenawan, and the older granite Laurentian.

The accessory mineral work is in general agreement with the conclusions reached by Leith, Lund, and Leith in that the results suggest a pre-Huronian granite in the Presque Isle area cut by a younger granite. This younger granite contains malacon and not the normal type of zircon found in the Keweenawan igneous rocks and is therefore considered pre-Keweenawan (probably equivalent to the Republic granite in age). Twelve samples of granite from this area were studied; half of these contained hyacinth, and half malacon. Both types of zircon are associated with apatite, ilmenite, leucoxene, sphene, and a minor amount of rutile.

Northern Complex of the Marquette district.—All workers have designated the igneous rocks of the Northern Complex pre-Huronian. Samples of the western granite, the syenite, the red granite northwest of the city of Marquette, and the granite gneiss near Big Bay were examined. The locations of the samples studied are shown in Figure 3. Hyacinth is the characteristic zircon in the various rock types within this area. This tends to conform with the conclusion reached by other workers that the igneous rocks of the Northern Complex are largely pre-Huronian. Most of the hyacinth is somewhat rounded, but an occasional grain is

euhedral. A pegmatite dike sampled in this area is characterized by malacon and may be related to a later granite.

Southern Complex of the Marquette district.—The field evidence gathered by many workers shows that the Southern Complex is not composed entirely of pre-Huronian igneous rocks. A younger granite intrudes the older granite, gneisses, and greenstones, and, in a few places, the Huronian series. This younger granite—the Republic granite of Lamey (1933a, p. 487-500)—is late Huronian. It has been impossible to date the granite more definitely because of the absence of known Keweenawan rocks in the area. The relative amounts of the pre-Huronian and post-Huronian granites have been a matter of controversy. Lamey believes that most of the granite of the Southern Complex is post-Huronian, whereas Dickey (1936, p. 317-340; 1938, p. 321-335) contends that much of the Southern Complex consists of pre-Huronian and pre-Middle Huronian igneous rocks.

Most of the samples for the present study were collected in the northern part of the Southern Complex fairly close to the Huronian series—in areas south of Palmer and Beacon, Michigan—although samples from other parts of the region were examined. Their locations are shown in Figure 3. The accessory minerals in the rocks of this region are apatite, ilmenite, leucoxene, magnetite, and zircon.

The gneiss in the area south of Palmer consists of thin alternating layers of biotite schist, gray granite, and red granite. Some samples show noticeable differences in the character of the accessory mineral suite in different facies. The biotite schist commonly contains hyacinth only, the gray granite a mixed suite, and the red granite malacon. Samples of gneiss which include these three phases contain a mixed hyacinth and malacon suite. The mixed accessory mineral assemblage may be the result of the intrusion of a granite containing malacon into an older rock characterized by hyacinth. From the field association it is evident that the red granite is later than the schist and gray granite, for the red granite cuts the other two phases. A similar situation is found in the area south of Beacon. This occurrence is discussed in more detail in the section on the Huronian granite.

The present accessory mineral study indicates that the younger granite of the region is characterized by malacon, whereas the older rocks contain hyacinth. It is difficult even to suggest the probable extent of these two granites in the Southern Complex.

The granite porphyry, a prominent member of the igneous sequence of the Southern Complex of the Marquette region, is pink to gray with large phenocrysts of orthoclase, microcline, and microperthite in a groundmass

of quartz, feldspar, biotite, and muscovite. The porphyry intrudes the granite gneiss and Keewatin schists. The relative ages of the granite porphyry and the Huronian sediments are not so evident. Dickey (1938, p. 321-335) presents evidence which suggests a post-Lower and pre-Middle Huronian age for the granite porphyry. The accessory mineral study of a few samples of this granite shows malacon, which occurs in the Lower Huronian sediments of the Marquette and Gogebic areas, in pre-Middle Huronian granites, and in Huronian intrusive rocks. The malacon suggests only that the granite porphyry is younger than the hyacinth-bearing granite but that it may be pre-Huronian or Huronian.

The Republic and Sturgeon River conglomerates were cited by Dickey as basal Huronian conglomerates which contain boulders of previously sheared granite porphyry in erosional contact with the granite porphyry.

The heavy mineral study of samples from the Republic locality shows that the "granite boulders" contain malacon and an occasional hyacinth, whereas the schistose banded sediment surrounding the "boulders" contains only very small well-rounded hyacinth grains. The small size of the hyacinth in the schist indicates that the sediment was originally very fine-grained. The granite directly beneath the "granite boulder conglomerate" is characterized by malacon similar to that in the "boulders". The occurrence of malacon in the "boulders" and the underlying granite may be explained in two ways: (1) The "boulders" were derived from the underlying granite, and the contact is erosional as suggested by Dickey; (2) the "boulders" are apophyses of the Republic granite in the Ajibik quartzite as suggested by Lamey.

The conglomerate exposed in the NE¼ of sec. 7, T. 42 N., R. 28 W. in the Sturgeon River trough, described by Clements, Smyth, and Bayley (1899, p. 462), is correlated as basal to the Sturgeon quartzite. Dickey (1936, p. 329) states that "The pebbles in the conglomerate appear to be composed for the most part of the red, fine-grained portions of the underlying granite-porphyry". He concludes that, inasmuch as pebbles of the granite porphyry occur in a basal Huronian conglomerate, the underlying porphyry must be pre-Huronian.

Samples were not obtained from the granite at this locality, but a sample of the conglomerate was studied which contained only hyacinth. Therefore the source granite must also be characterized by hyacinth. This suggests that the granite from which the Sturgeon River conglomerate was derived is not the same as the granite porphyry in other parts of the region, for the typical granite porphyry as described by Dickey is characterized by malacon.

Lamey (1933b, p. 3-4) studied the accessory minerals in samples from the Southern Complex and kindly loaned the slides to the writers. Nine-

teen samples from outcrops along the south side of the Marquette trough were studied. These are characterized by malacon or a mixture of malacon and hyacinth, indicating the abundance of the malacon-bearing granite in this area. Whether it is pre-Huronian or Huronian is not known.

Lake Pelissier area.—A red granite exposed on a prominent hill just west of Lake Pelissier (Lake Mary) in secs. 8, 9, and 16, T. 47 N., R. 25 W. (Fig. 3), is overlain unconformably by a conglomerate which contains pebbles of the underlying granite. The conglomerate, which dips away from the granite at an angle of about 15 degrees, was mapped as basal to the Mesnard quartzite by Van Hise and Bayley (1897, p. 239-240). The pebbles in the conglomerate consist of vein quartz, green schist, jasper, chert, quartzite, and granite. The red granite and the red granite pebbles in the conglomerate are characterized by malacon.

SUMMARY OF THE PRE-HURONIAN GRANITE

The pre-Huronian includes granites of two ages—an older characterized by hyacinth and a younger characterized by malacon. Malacon also occurs in igneous rocks which are intrusive into the Huronian; therefore it is not possible to distinguish some of the pre-Huronian from igneous rocks of Huronian age on a basis of the zircon contained. The hyacinth-bearing granite, however, is pre-Huronian and always older than the malacon-bearing granite.

HURONIAN SEDIMENTARY ROCKS

GENERAL STATEMENT

The Huronian sedimentary rocks were studied in 214 samples from 20 different formations, and the results were compared with studies of more than 300 samples of igneous rocks from the same areas. These samples were collected in four districts where Huronian strata are well exposed: the Penokee-Gogebic, Marquette, Felch Mountain and Florence areas. The Huronian rocks consist of quartzites, slates, graywackes, dolomites, and iron formations and occur in these districts in synclines where they have been protected during the long erosional periods since deposition. For a detailed discussion of the lithology and stratigraphy of the Huronian, *see* Van Hise and Leith (1911), and the original sources mentioned therein.

HEAVY MINERALS

The heavy minerals in the Huronian sedimentary formations are apatite, zircon, rutile, anatase, sphene, hornblende, chlorite, biotite, epidote, grunerite, garnet, tourmaline, diopside, andalusite, cyanite, and the opaque minerals ilmenite, leucoxene, and pyrite. They may be genetically grouped into three classes: (1) authigenic, (2) detrital-inclusion (transported

within detrital quartz grains and freed by crushing) according to Mackie (1896, p. 148-172) and Tyler (1936, p. 55-84), and (3) detrital.

AUTHIGENIC AND DETRITAL-INCLUSION SUITES

Inasmuch as all Huronian formations have suffered more or less intense metamorphism the development of secondary minerals is not surprising. These should be recognized and considered separately from the detrital suite. Mineral grains showing undoubted evidence of abrasion belong in the detrital suite. Minerals such as hornblende, chlorite, and biotite generally do not show the results of abrasion even when transported by water for some distance. If rounding is the sole criterion for distinguishing detrital from authigenic minerals, certain minerals may be excluded from the detrital suite which in reality belong there. On the other hand, roundness of a mineral particle is not in itself infallible evidence that the grain is detrital, for round to elliptical grains of minerals are common in igneous rocks. However, if the grains are rounded, as well as pitted and frosted, there can be little doubt that they are detrital. Alteration products such as leucoxene may be detrital particles or may develop authigenically.

Although it is often difficult to distinguish detrital from authigenic minerals, it is more difficult to distinguish between authigenic and detrital-inclusion minerals. Thin-section study may show whether a particular mineral is authigenic or inclusion, but, if a rock has been recrystallized, and the outline of the original detrital grain has been lost, the detrital-inclusion and authigenic minerals cannot be distinguished. The situation is complicated by the fact that a given mineral may occur in two generations—as an inclusion within detrital quartz or feldspar grains and as an authigenic mineral developed by metamorphism. Although it is important in the interpretation of the history of a sediment to determine the heavy minerals in the detrital-inclusion suite the practical difficulties are such that this information could not be obtained.

The following minerals are present in the Huronian sedimentary formations as authigenic or detrital-inclusion minerals, or both. This group of minerals throws little light upon the origin of the Huronian sedimentary formations.

ANATASE: Two varieties are present—light-blue to colorless and yellow. The anatase occurs as tabular euhedral grains or as incompletely developed crystals which show no evidence of abrasion. The mineral is probably entirely authigenic. A few crystals are attached to leucoxene. Zoning of the crystals is general.

ANDALUSITE: Rare in the Middle Huronian iron formation, Keyes Lake, and Sturgeon quartzites. Colorless nonpleochroic crystals and irregular grains are common. No evidence of abrasion noted, which suggests that the mineral is authigenic. The grains contain occasional colorless and opaque inclusions.

APATITE: Occurs rarely as round to elliptical grains, commonly as euhedral-crystals, and predominantly as irregular grains. It is generally clear and practically free of

inclusions, although occasional cored-apatite grains are present. Crystals and irregular grains occur in the iron formations and account for at least part of the phosphorous in the ores. The rarity of round to elliptical detrital grains suggests three alternative explanations: (1) Detrital apatite has been recrystallized during metamorphism, (2) secondary apatite has been introduced into the sediments after deposition, or (3) the apatite occurs as inclusions within detrital quartz and feldspar grains. The apatite in the Huronian sediments is probably not all of the same origin.

BIOTITE: Occurs as dark-green to brown circular to irregular flakes which do not indicate detrital origin, for the same shape is common in igneous rocks. Most of the grains are remarkably free from inclusions, although occasional colorless and opaque inclusions are present.

CHLORITE: Characterized by green circular to irregular flakes which are not indicative of detrital origin, for the same shape is common in igneous rocks. Opaque inclusions are rather common.

EPIDOTE-CLINOZOISITE: A variety of composition within this series is well represented in the Huronian. The colorless to light-green grains are irregular, and some are clouded by fine opaque and colorless inclusions. No evidence of abrasion was noted.

GARNET: Occurs as colorless to pink angular grains and as dodecahedral crystals. No abraded or etched garnets were seen. The garnet is probably secondary, for the samples containing garnet were collected from contact-metamorphosed sediments near basic intrusives. In some samples garnet is visible in hand specimen. Opaque and colorless inclusions are common.

GRUNERITE: Occurs as light-green to colorless fibrous lath-shaped secondary grains. Many grains contain colorless or opaque inclusions.

HORNBLENDE: Forms ragged unaltered lath-shaped grains containing black, brown, and colorless inclusions. Color ranges from dark to light green. No evidence of detrital origin was noted.

KYANITE: Noted only in the Breakwater quartzite. The mineral forms rectangular to irregular colorless grains with good basal and pinacoidal cleavage. Some of the grains contain dustlike inclusions.

RUTILE: Occurs in two forms: (1) commonly as sheafs of acicular foxy-red crystals ranging from transparent to opaque, and (2) as brown euhedral crystals. The rutile is of authigenic or detrital-inclusion origin. Geniculated twins are rather common.

SPHENE: Very rare in the Huronian sediments. Occurs as euhedral clear yellowish-green crystals practically free from inclusions. The sphene probably occurs as inclusions within the quartz grains. No detrital sphene was discovered in the sediments.

TOURMALINE: Perfectly formed crystals ranging from colorless or light brown to bluish green or greenish brown are numerous in most of the samples from the Huronian.

DETRITAL SUITE

The heavy minerals known to be detrital are as follows:

LEUCOXENE: Occurs both as detrital and authigenic earthy, white to yellow-brown grains.

OPAQUE MINERALS: Consist largely of ilmenite and perhaps martite—magnetite and pyrite were not counted—although several other species probably occur in varying quantities. The ilmenite may be seen in all stages of alteration to leucoxene. The opaque minerals range from spherical to angular in shape. Grains in the coarser sediments show most evidence of abrasion.

RUTILE: Present as well-rounded dark to greenish-brown grains.

TOURMALINE: Grains, spherical to elliptical, are generally somewhat larger than the associated heavy mineral grains. Most are brown; a few are green or blue. Etching of detrital tourmaline is common, but no secondary enlargement was seen.

ZIRCON: Dominant type in the Huronian sedimentary rocks is the hyacinth variety which ranges from deep purple through pink to colorless. Large grains are generally

a deep purple, brown, or pink, whereas small grains range from light-purple to colorless. The larger grains are usually spherical to elliptical and pitted and frosted, but smaller grains show little evidence of abrasion. The malacon variety occurs as small colorless grains. Malacon is most abundant in the fine-grained sediments probably because the original grains were rather small. Their rarity in the Huronian sedimentary rocks may be chiefly due to the fact that malacon is rather soft as compared to hyacinth and thus was largely eliminated during transportation of the sediment.

Secondary growths upon rounded grains of zircon such as described by Trueman (1912, p. 249) were noted in the Sturgeon quartzite. The secondary zircon has been added chiefly to the rounded ends of the grains to form a new set of pyramidal faces. Occasionally the new growth completely envelops the original grain. Secondary growths upon the prismatic faces as described by Butterfield (1936, p. 511-516) from the Millstone grit do not occur in the samples studied.

Table 4 gives the relative percentages of the heavy minerals in 19 Huronian sediments and shows the relative proportions of the various heavy minerals available for distribution to later sedimentary rocks. The frequency of each mineral was determined by counting at least 300 grains per slide. No satisfactory distinction could be made, while counting, between the detrital, detrital-inclusion, and authigenic minerals, and therefore all are shown in the same tables.

The detrital heavy minerals from thousands of feet of Huronian sedimentary rock over wide areas are so uniform that no formation can be distinguished on this basis. The variation in grain size and degree of sorting of the sediment do not greatly affect the distribution of the detrital heavy minerals. In fact, the variation within a given slate is as great, and within the same limits, as within a given quartzite. The average grain size of the heavy minerals of the Huronian shows a direct correlation with the grain size of the sediment.

The use of detrital accessories by weight as an index of a given formation is precluded by the abundance of authigenic minerals. Since it is impossible to separate and, in some cases, even to distinguish detrital from secondary minerals, a comparison of the weight relations of the detrital heavy minerals in the various formations is of little value.

Correlation of the sedimentary formations, which is one of the major problems of the Huronian, can hardly be based therefore, upon heavy minerals. A more detailed study might lead to the discovery of definite horizons within the Huronian characterized by a distinctive suite, but this seems unlikely. However, the uniformity in both the mineralogical composition and varietal characteristics of the detrital heavy minerals throughout the Huronian may be used to distinguish the Huronian sedimentary rocks from those of other systems.

SOURCE OF HURONIAN SEDIMENTS

Van Hise and Leith suggested, on the basis of field study, that the Huronian sediments were largely derived locally from granites, gneisses,

TABLE 4.—*Relative per cent of heavy minerals*

In the Huronian sediments on the south shore of Lake Superior

	Sample no.	Zircon	Tourmaline (detrital)	Tourmaline (crystals)	Apatite	Anatase	Rutile	Sphene	Leucoxene	Opaque minerals	Chlorite	Biotite	Hornblende	Grunerite	Epidote	Garnet	Kyanite	Andalusite
Michigamme slate	44a	x	x	x	x	x	....	....	....	78	5	....	....	....	....	17	....	....
	44	x	....	x	....	x	....	....	....	100	....	....	....	x	....	....	....	....
	45	3	....	8	78	....	....	....	5	6	....	....	....	....	....	....	....	....
	46	4	....	19	65	....	....	....	9	3	....	....	....	....	....	....	....	....
	47	45	...	x	x	10	....	....	....	45	....	....	....	....	....	....	....	....
	48	24	....	....	9	24	....	....	....	43	....	....	....	....	....	....	....	....
	49	5	....	1	54	3	....	....	....	37	....	....	....	....	....	....	....	....
	165	3	x	5	22	....	....	....	....	70	....	....	....	....	....	....	....	....
Bijiki schist	51	....	....	....	....	....	....	....	....	11	88	1	....	....	....	x	....	....
	52	....	....	....	....	....	....	....	....	6	91	....	....	x	....	3	....	....
Goodrich quartzite	1	x	....	....	1	....	....	....	....	1	4	94	....	....	....	....	....	....
	2	x	....	18	1	....	....	....	....	3	74	....	....	4	....	....	....	....
	3	x	....	....	x	....	....	4	....	2	28	x	....	65	....	1	....	....
	12	x	....	....	43	....	....	....	....	6	....	51	....	....	....	....	....	....
	13	x	....	x	x	....	....	....	....	x	93	7	....	....	....	x	....	....
	14	x	....	x	x	....	....	....	....	x	100	x	....	....	....	x	....	....
	15	x	....	....	x	....	....	....	....	2	98	x	....	....	....	x	....	....
	17	x	....	....	x	....	....	....	....	6	74	12	....	7	....	1	....	....
	18	x	....	....	x	....	....	....	....	3	90	....	....	5	....	2	....	....
	19	x	....	x	x	....	....	....	....	1	51	47	....	1	....	x	....	....
	20	x	....	x	x	....	....	....	....	6	70	....	....	13	....	11	....	....
	21	x	....	....	x	....	....	....	....	2	20	....	....	57	....	21	....	....
	23	x	....	....	x	....	....	....	....	3	18	....	....	60	....	19	....	....
	24	x	....	....	x	....	....	....	....	2	35	....	....	56	....	7	....	....
	25	x	....	....	x	....	....	....	....	4	19	....	....	72	....	5	....	....
	26	x	....	....	x	....	....	....	....	11	22	....	....	66	....	1	....	....
	27	x	....	....	x	....	....	....	....	4	8	....	....	88	....	....	....	....
	28	x	....	....	x	....	....	....	....	10	3	....	....	87	....	....	....	....
	29	x	....	....	x	....	....	....	....	11	1	....	....	88	....	....	....	....
	145	x	....	x	x	....	....	x	....	100	....	....	....	....	....	....	....	....
	146	x	....	x	x	....	....	....	....	100	....	....	....	....	....	....	....	....
	147	x	....	x	x	....	....	....	....	100	....	....	....	....	....	....	....	....
Negaunee formation	7	x	....	x	....	....	....	....	x	100	x	x	....	x	....	....	....	....
	140	8	....	x	....	x	....	....	x	91	....	....	1	....	....	....	....	....
Siamo slate	9	x	....	....	....	....	....	....	....	2	1	....	....	93	....	4	....	....
	11	x	....	....	....	....	....	x	....	5	x	....	....	95	....	....	....	....
	30	x	....	x	....	....	....	....	....	....	x	100	....	....	....	....	....	....
	38	x	....	x	....	....	....	....	....	....	12	88	....	....	....	....	....	....
	39	x	....	....	....	....	....	....	....	x	7	91	....	....	2	....	....	....
	40	x	....	....	....	....	....	....	....	....	29	68	....	....	3	....	....	....
	41	x	....	1	....	....	....	....	....	2	11	86	....	....	....	....	....	....
	42	x	....	x	....	....	....	....	....	1	5	94	....	....	....	....	....	....
	43	78	....	....	x	....	....	....	....	22	....	....	....	....	....	....	....	....
	135	x	....	x	....	....	....	....	....	97	3	....	....	....	....	....	....	....
	136	x	....	x	....	....	....	....	x	100	....	....	....	....	....	....	....	....
	137	2	x	1	....	....	....	....	2	91	4	....	....	x	....	....	....	....
	151	4	....	6	28	....	....	....	38	2	22	....	....	....	....	....	....	....
	153	....	....	....	x	....	....	....	2	40	58	....	....	....	....	....	....	....
	159	1	....	1	1	....	....	....	....	3	....	94	....	....	....	....	....	....

x less than 1 per cent.

TABLE 4.—*Relative per cent of heavy minerals*—Continued

In the Huronian sediments on the south shore of Lake Superior

	Sample no.	Zircon	Tourmaline (detrital)	Tourmaline (crystals)	Apatite	Anatase	Rutile	Sphene	Leucoxene	Opaque minerals	Chlorite	Biotite	Hornblende	Grunerite	Epidote	Garnet	Kyanite	Andalusite
Ajibik quartzite	30a	x	....	x	x	....	....	....	x	10	76	14	....	....	....	....	....	....
	32	x	....	....	x	....	....	....	1	85	14	....	....	....	....	x	....	....
	33	3	....	....	5	....	....	....	6	28	58	....	....	....	....	....	....	....
	34	18	....	....	1	....	....	x	5	75	....	....	....	....	x	1	....	....
	35	3	....	1	9	....	1	....	2	16	68	x	....	....	....	....	....	....
	126	55	2	....	1	....	....	x	29	13	....	....	....	....	....	....	....	....
	127	24	2	....	6	1	....	....	12	55	....	....	....	....	....	....	....	....
	128	20	x	x	3	....	....	....	11	61	5	....	....	x	....	....	....	....
	129	31	8	....	6	9	1	x	20	25	x	....	....	....	....	x	....	....
	131	x	....	....	x	....	....	....	6	x	94	....	....	....	....	....	....	....
	154	14	x	4	9	....	....	....	27	37	....	....	9	....	....	....	....	....
	156	2	x	....	32	....	x	x	1	36	27	2	....	....	....	....	....	....
	170	19	....	2	8	....	5	....	43	14	9	....	x	....	....	....	....	....
	171	29	x	1	4	....	23	....	22	19	1	1	....	....	....	....	....	....
	172	20	x	2	8	....	11	1	40	15	2	....	1	....	....	....	....	....
	173	2	....	....	1	x	....	....	1	9	87	x	....	....	....	....	....	....
	174	1	....	x	3	x	....	....	x	33	63	....	....	....	x	....	....	....
	175	x	....	x	x	....	....	....	x	5	18	65	....	1	....	11	....	....
	176	x	....	x	x	....	....	....	x	1	8	80	x	2	....	9	....	....
	177	2	....	x	x	....	....	....	3	29	16	50	....	....	....	....	....	....
Wewe slate	123	x	....	x	1	....	17	x	x	82	x	....	x	....	....	....	....	....
Kona dolomite	86	x	....	1	....	x	x	....	....	99	....	....	....	....	....	....	....	....
	113	x	....	7	....	....	....	....	3	90	....	....	x	....	....	....	....	x
Mesnard quartzite	54	18	....	4	2	....	....	....	50	20	x	....	6	....	x	x	....	....
	56	20	x	x	1	....	x	....	39	40	....	....	....	....	x	....	....	....
	57	21	1	x	x	....	....	....	63	15	....	x	x	....	x	....	....	....
	58	17	x	....	....	....	....	....	16	67	....	....	x	....	....	x	....	....
	59	49	x	....	1	....	....	....	16	34	....	....	....	....	....	x	....	....
	60	44	2	x	8	....	....	....	24	22	....	....	x	....	....	....	....	....
	62	52	2	x	x	....	....	....	24	14	....	....	8	....	x	....	....	....
	63	31	....	x	....	....	....	....	29	39	....	....	1	....	....	....	....	....
	64	61	x	x	....	....	....	....	36	3	x	....	x	....	x	x	....	....
	65	15	....	....	....	....	....	....	11	74	....	....	....	....	....	....	....	....
	66	55	x	x	x	....	....	....	34	11	x	....	x	....	....	....	....	....
	67	49	8	x	....	....	....	....	42	1	....	....	x	....	x	....	....	....
	68	44	3	x	x	....	....	....	49	4	....	....	x	....	....	x	....	....
	69	36	....	....	1	....	x	....	63	....	....	....	....	....	....	....	....	....
	70	43	3	x	....	....	....	....	47	7	x	....	....	....	....	....	....	....
	71	56	x	9	x	....	....	....	32	3	....	....	....	....	....	....	....	....
	73	40	1	x	x	....	....	....	21	38	x	....	x	x	....	....	....	....
	74	54	1	x	x	....	1	....	32	12	....	....	x	....	....	x	....	....
	75	5	x	6	1	....	....	....	7	81	x	....	x	....	....	....	....	....
	76	17	1	1	1	....	....	....	13	66	1	x	....	....	....	....	....	....
	77	2	x	x	x	....	....	....	3	95	....	....	....	....	....	....	....	....
	81	x	....	x	1	....	x	....	70	8	21	....	....	....	....	x	....	....
	83	x	....	x	x	....	....	....	59	21	20	....	....	....	....	....	....	....
	85	25	....	....	30	....	x	....	45	....	....	....	....	....	....	....	....	....
	94	6	....	2	6	x	....	....	4	82	....	....	....	....	....	....	....	....
	95	12	....	4	9	....	....	....	3	72	x	....	....	....	....	....	....	....
	96	x	....	....	x	....	....	....	5	73	22	....	....	....	....	....	....	....

x less than 1 per cent.

TABLE 4.—*Relative per cent of heavy minerals*—Continued

In the Huronian sediments on the south shore of Lake Superior

	Sample no.	Zircon	Tourmaline (detrital)	Tourmaline (crystals)	Apatite	Anatase	Rutile	Sphene	Leucoxene	Opaque minerals	Chlorite	Biotite	Hornblende	Grunerite	Epidote	Garnet	Kyanite	Andalusite
Mesnard quartzite continued	97	x	x	x	1	....	....	....	69	30	....	....	....	....	....	....	....	....
	98	1	x	x	4	....	....	....	4	91	....	....	....	....	....	....	....	....
	99	10	1	3	2	....	....	....	5	79	x	x	....	....	....	....	....	....
	100	17	1	2	2	....	x	....	2	76	....	....	....	....	....	....	....	....
	101	6	x	1	x	....	....	....	3	90	x	x	....	....	....	....	....	....
	102	8	x	....	....	....	....	....	1	91	....	....	x	....	....	....	....	....
	103	4	x	2	3	....	....	....	9	82	....	....	....	....	....	....	....	....
	107	23	x	....	13	....	1	....	49	....	8	1	4	....	....	1	....	....
	109	46	1	x	....	....	x	....	46	7	x	....	x	....	....	....	....	....
	110a	4	....	x	....	....	....	....	....	96	....	....	....	....	....	....	....	....
	110b	6	....	....	x	....	....	....	1	93	....	....	....	....	....	....	....	....
	124	11	x	x	x	....	....	....	x	89	....	....	....	x	....	x	....	....
	124a	6	....	....	x	x	....	x	1	93	....	....	....	....	....	....	....	....
	124b	29	....	16	x	x	4	....	26	25	....	x	....	....	....	....	....	....
Tyler slate	289	3	....	....	....	....	....	....	....	97	....	....	....	....	....	....	....	....
	358	x	....	1	x	....	....	....	....	4	....	58	....	37	....	....	....	....
	360	2	....	7	1	....	....	....	x	33	....	57	....	....	....	....	....	....
	361	3	....	9	3	....	....	....	x	50	....	35	....	....	....	....	....	....
	362	1	....	9	4	....	....	....	....	66	....	20	....	....	....	....	....	....
	363	5	....	8	4	....	x	....	2	46	....	35	....	....	....	....	....	....
	364	2	....	6	3	....	....	....	3	17	....	69	....	....	....	....	....	....
	368	56	....	x	29	....	....	....	4	11	....	....	....	....	....	....	....	....
	369	16	x	2	2	....	....	x	....	41	....	39	....	....	....	....	....	....
	388	8	....	x	7	....	....	....	....	62	....	23	....	....	....	....	....	....
	389	37	....	x	24	....	....	....	1	38	....	x	....	....	....	....	....	....
	390	15	....	x	16	....	....	....	....	54	....	15	x	....	....	....	....	....
	391	35	....	x	21	....	....	....	3	35	x	6	....	....	....	....	....	....
	392	9	x	3	16	....	....	....	4	41	....	27	....	....	....	....	....	....
Ironwood iron formation	303	1	....	x	x	....	....	....	5	94	....	....	....	....	....	....	....	....
	308	2	....	....	....	x	x	....	3	95	....	....	....	....	....	....	....	....
	309	x	....	....	....	....	38	....	62	....	....	....	....	....	....	....	....	....
	310	6	....	....	....	....	....	....	63	31	....	....	....	....	....	....	....	....
	311	x	....	....	....	x	....	....	100	x	....	....	....	....	....	....	....	....
	312	x	....	....	....	....	....	....	88	12	x	x	....	....	....	....	....	....
	373	x	....	....	....	....	....	....	x	100	x	....	x	....	....	x	....	....
	374	x	....	....	....	....	....	....	....	100	....	....	....	....	....	....	....	....
	376	x	....	x	....	....	....	....	x	100	....	....	....	....	....	....	....	x
	377	x	....	x	....	....	....	....	x	100	....	....	....	....	....	....	....	....
Palms quartz slate	234	17	5	1	29	....	1	....	12	35	....	....	....	....	x	....	....	....
	234a	17	....	x	32	....	....	....	30	21	....	....	....	....	....	....	....	....
	235	43	8	....	1	....	2	....	16	30	....	....	....	....	....	....	....	....
	236	48	11	x	2	....	2	....	20	17	....	....	....	....	....	....	....	....
	240	39	9	2	1	....	1	....	39	9	....	....	....	....	....	....	....	....
	241	8	1	....	2	....	....	....	4	85	....	....	....	....	....	....	....	....
	242	42	8	3	x	....	2	....	11	34	....	....	....	....	....	....	....	....
	243	13	7	3	1	....	....	....	5	71	....	....	....	....	....	....	....	....
	244	41	4	x	1	....	1	....	13	40	....	....	....	....	....	....	....	....
	245	26	4	1	1	....	x	....	10	58	....	....	....	....	....	....	....	....
	246	14	6	3	1	x	....	....	16	60	....	....	....	....	....	....	....	....
	247	46	3	2	x	....	2	....	18	29	....	....	....	....	....	....	....	....

x less than 1 per cent.

TABLE 4.—*Relative per cent of heavy minerals*—Continued

In the Huronian sediments on the south shore of Lake Superior

	Sample no.	Zircon	Tourmaline (detrital)	Tourmaline (crystals)	Apatite	Anatase	Rutile	Sphene	Leucoxene	Opaque minerals	Chlorite	Biotite	Hornblende	Grunerite	Epidote	Garnet	Kyanite	Andalusite
Palms quartz slate continued	248	1	....	....	....	....	....	....	....	99	....	....	....	....	....	....	....	....
	249	x	....	....	....	....	....	....	....	100	....	....	....	....	....	....	....	....
	250	3	1	1	....	....	x	....	1	94	....	....	....	....	....	....	....	....
	251	7	4	1	3	....	....	....	6	79	....	....	....	....	....	....	....	....
	252	25	....	....	x	....	....	....	3	72	....	....	....	....	....	....	....	....
	253	3	1	x	1	....	....	....	5	90	....	....	....	....	....	....	....	....
	254	32	6	4	5	....	x	....	24	29	....	....	....	....	....	....	....	....
	255	....	....	....	....	....	....	....	2	98	....	....	....	....	....	....	....	....
	256	2	x	1	1	....	....	....	2	94	....	....	....	....	....	....	....	....
	257	2	1	x	x	....	....	....	1	96	....	....	....	....	....	....	....	....
	258	1	x	....	....	....	....	....	x	99	....	....	....	....	....	....	....	....
	259	11	4	1	x	....	....	....	7	77	....	....	....	....	....	....	....	....
	260	12	1	....	....	....	....	....	9	78	....	....	....	....	....	....	....	....
	261	12	1	x	1	....	....	....	5	81	....	....	....	....	....	....	....	....
	262	1	x	....	....	....	....	....	1	98	....	....	....	....	....	....	....	....
	263	1	....	x	x	....	....	....	5	94	....	....	....	....	....	....	....	....
	305	27	x	x	....	....	....	x	67	6	....	....	....	....	x	x	....	....
	306	46	x	1	....	x	....	....	48	5	....	....	....	....	x	x	....	....
	307	3	....	x	....	x	....	....	97	....	....	....	....	....	....	....	....	....
	327	16	....	31	5	....	....	....	1	47	....	....	....	....	....	....	....	....
	329	12	....	35	28	x	....	....	1	24	....	....	....	....	....	....	....	....
	333	x	....	....	1	....	....	....	3	96	....	....	....	....	....	....	....	....
	334	1	....	....	25	....	....	....	6	68	....	....	....	....	....	....	....	....
	335	4	....	....	7	....	....	....	13	76	....	....	....	....	....	....	....	....
	336	1	....	....	3	....	....	....	4	92	....	....	....	....	....	....	....	....
	337	2	....	....	4	....	....	....	38	56	....	....	....	....	x	....	....	....
	338	2	x	....	2	....	....	....	5	91	....	....	....	....	....	....	....	....
	339	3	1	x	1	....	....	....	2	93	....	....	....	....	....	....	....	....
	340	72	3	6	2	....	x	....	3	14	....	....	....	....	....	x	....	....
	341	45	7	19	6	....	....	....	11	12	....	....	....	....	....	....	....	....
	342	23	2	23	4	x	....	....	8	40	....	....	....	....	x	....	....	....
	343	28	3	15	x	x	....	....	13	41	....	....	....	....	....	....	....	....
	344	21	1	7	x	x	....	....	6	65	....	....	....	....	....	....	....	....
	345	73	x	9	x	x	....	....	9	9	....	....	....	....	....	....	....	....
	346	42	5	15	1	....	....	....	13	24	....	....	....	....	....	x	....	....
Bad River dolomite	387	12	....	2	x	....	....	....	x	86	....	....	....	....	....	....	....	....
Sunday quartzite	217	12	x	1	35	15	....	....	18	16	1	....	2	....	....	....	....	....
	219	62	3	x	10	....	x	....	9	16	....	....	....	....	....	....	....	....
Copps slate	196	3	....	7	44	....	....	....	5	41	x	....	....	....	....	....	....	....
	215	4	....	1	....	....	....	....	5	30	x	x	....	....	60	....	....	....
Sturgeon quartzite	194	51	....	....	40	....	....	....	2	6	....	x	1	....	x	....	....	....
	204	3	....	....	3	....	....	....	x	2	....	....	90	....	2	....	....	....
	205	14	....	2	17	....	x	....	18	42	2	x	3	....	2	x	....	....
	206	7	....	....	2	....	....	....	2	29	1	21	1	....	37	....	....	....
	207	6	....	2	x	....	x	....	....	34	9	....	9	....	40	....	....	....
	208	20	....	7	8	....	x	....	3	3	2	1	17	....	39	....	....	....
	209	3	....	x	1	....	....	....	....	95	1	x	....	....	x	....	....	....
	210	5	....	x	9	....	....	....	x	54	5	x	2	....	25	....	....	x

x less than 1 per cent.

TABLE 4.—*Relative per cent of heavy minerals*—Continued

In the Huronian sediments on the south shore of Lake Superior

	Sample no.	Zircon	Tourmaline (detrital)	Tourmaline (crystals)	Apatite	Anatase	Rutile	Sphene	Leucoxene	Opaque minerals	Chlorite	Biotite	Hornblende	Grunerite	Epidote	Garnet	Kyanite	Andalusite
Sturgeon quartzite continued	464	45	....	....	4	1	x	....	4	36	4	....	2	....	4	....	....	....
	465	10	....	2	2	....	....	....	6	25	10	x	7	....	38	....	....	....
	466	8	....	....	8	....	....	....	6	5	....	x	26	....	47	....	....	....
Vulcan formation	201	x	....	....	1	x	....	x	x	14	85	....	....	....	....	x	....	....
Breakwater quartzite	475	x	x	....	x	....	....	x	....	95	x	....	....	....	....	....	5	....
	476	x	....	x	x	....	....	x	....	97	1	....	....	....	....	....	2	....
	477	x	x	x	x	....	....	x	....	97	....	....	....	....	....	....	3	....
Keyes Lake quartzite	458	34	x	x	....	....	....	....	62	4	....	....	x	....	....	....	....	....
	459	4	x	33	....	....	....	....	35	28	....	....	....	....	....	....	....	x
	460	16	1	7	....	....	....	....	64	12	....	....	x	....	....	....	....	....
	461	23	....	12	1	....	....	....	44	20	x	....	....	....	....	....	....	....
	462	14	1	14	2	....	....	....	17	52	....	....	....	....	....	....	....	....

x less than 1 per cent.

and greenstones. They noted particularly that the basal Huronian rocks contain pebbles and finer detritus definitely traceable to the rocks of the underlying basement.

The detrital heavy minerals in the Huronian series consist of zircon, tourmaline, rutile, leucoxene, and opaque minerals. Unfortunately, as a suite, these minerals do not connote a particular source, for they may be derived from almost any igneous or sedimentary rock. Therefore, one must turn to varietal characteristics of the individual minerals. Of the minerals noted, only tourmaline and zircon have sufficiently distinctive varietal characteristics to be of any value. Detrital tourmaline, however, is comparatively rare in the Huronian rocks, leaving zircon as the only mineral which may indicate the source of the Huronian sedimentary rocks.

The Huronian rocks are characterized by the dominance of hyacinth which comes from the older rocks. It is both interesting and significant to note that the common metamorphic minerals such as garnet, kyanite, andalusite, and staurolite are absent as detritals in the Huronian sedimentary rocks. Their absence suggests that no terrane containing these minerals contributed sediments to the Huronian. Possibly these minerals were once detrital in the Huronian sediments, but later solution completely removed them.

HURONIAN GRANITE

GENERAL STATEMENT

According to Allen and Barrett (1914, p. 50-54), post-Huronian granite occurs in the Gogebic, Marenisco, Turtle, Vieux Desert, and Conover districts. Swanson (1930), Zinn (1931), and Lamey (1931, p. 288-295) report post-Huronian granite from the Marquette district, Lamey (1933a, p. 490-492) from the Felch Mountain district, Clements, Smyth, and Bayley (1899, p. 164, 190-198) from the Crystal Falls district, and Van Hise and Leith (1911, p. 323, 344) from the Florence and Menominee districts. No positive evidence has been presented for the age of these granites beyond the fact that they intrude Lower, Middle, or Upper Huronian sediments. Thus the granites may be Huronian, post-Huronian—pre-Keweenawan, post-Middle Keweenawan, or post-Keweenawan.

Many writers, failing to recognize the possibility of an orogeny marking the close of the Huronian, have correlated all the late granite in this region with the Keweenawan period of diastrophism. Early workers in the area noted that the Huronian series is more highly metamorphosed than the Keweenawan sediments (Van Hise and Leith, 1911, p. 424). This difference in metamorphism suggests a considerable time break between the two series.

The Huronian and Keweenawan series appear to be conformable in the central part of the Penokee-Gogebic range, but at the east and west ends of the district the Keweenawan gradually cuts across thousands of feet of Huronian sediments and finally comes in contact with the pre-Huronian basement. At the east end of the district the closely folded and highly metamorphosed Huronian of the Turtle and Marenisco ranges strikes into and passes under the gently dipping basal Keweenawan sandstone. In the Ramsey and Wakefield area and in T. 47 N., Rs. 43 and 44 W., extensive faulting accompanied pre-Keweenawan folding, and the fault blocks were later beveled by the basal Keweenawan unconformity. Thus, the Huronian series suffered folding and faulting as well as regional metamorphism before the deposition of the basal Keweenawan sandstone. This orogeny is thought to have been accompanied by the intrusion of a granite which will be referred to in this paper as the Huronian granite. The concept of a post-Huronian—pre-Keweenawan orogeny is not new, for Van Hise and Leith (1911, p. 234) state: "The time gap between the Huronian series and the Keweenawan series must have been sufficient for a widespread orographic movement and deep denudation".

In order to determine the heavy accessory mineral suite characteristic of the late granite, samples were collected and studied from nine localities where granite intrudes Lower, Middle, or Upper Huronian. These samples

should be considered types only in the sense that their age relative to the Huronian is known. The localities are as follows: (*See* Table 1 for correlation.)

1. Pegmatite dike, Michigamme slates (Upper Huronian) on island in Lake Michigamme, SW¼ of NW¼ sec. 34, T. 48 N., R. 30 W.
2. Granite dike cutting Siamo slate (Middle Huronian) at Lake Palmer, SW¼ of NE¼ sec. 25, T. 47 N., R. 27 W.
3. Granite dike cutting the Vulcan iron formation (Middle Huronian) at the Groverland mine, Felch district, near center sec. 31, T. 42 N., R. 21 W.
4. Granite cutting the Upper Huronian, Crystal Falls district, sec. 21, T. 42 N., R. 32 W. Studied by Marsden (1932-1933, p. 4-6).
5. Granite dike cutting the Sturgeon quartzite (Lower Huronian) at Randville, NW¼ of SW¼ sec. 34, T. 42 N., R. 30 W.
6. Granite dike cutting the Randville dolomite (Lower Huronian), Felch district, NW¼ of NE¼, sec. 35, T. 42 N., R. 28 W.
7. Dikes cutting the Lower and Middle Huronian south of Palmer, secs. 31 and 32, T. 47 N., R. 26 W.
8. Granite cutting the Upper Huronian south of Crystal Falls, NE¼, sec. 19, T. 42 N., R. 31 W.
9. Dikes cutting Goodrich quartzite (Upper Huronian) southeast of Lake Michigamme, sec. 3, T. 47 N., R. 30 W.

HEAVY ACCESSORY MINERALS

The heavy accessory minerals in the Huronian granite are apatite, malacon, sphene, garnet, rutile, ilmenite, and leucoxene. These minerals have the same characteristics as those described in connection with the pre-Huronian granite.

MARQUETTE REGION

General statement.—Huronian granite occurs in several localities along the south side of the Marquette trough (Fig. 3). Lamey (1931, p. 288-295; 1933a, p. 490-492; 1934, p. 248-263) cites the occurrence of numerous dikes cutting various Huronian formations and describes the accompanying metamorphism. He believes that much of the granite of the Southern Complex is post-Huronian and terms it the Republic granite. It is impossible to date this granite more accurately because Keweenawan rocks are not known to occur in the Marquette region. Dickey (1936, p. 317-340) disagreed with Lamey on the relative importance of the Archean and Huronian granites. More recently Dickey (1938, 321-335) has suggested a post-Lower and pre-Middle Huronian granite in this area. The present study of the accessory minerals of the igneous rocks of this area is not extensive enough to attempt to restrict the areas of Archean and post-Archean granites.

Beacon area.—The area south of Beacon, Michigan (Fig. 3), has been studied by Lamey and Dickey, and they agree that much of the granite

is Huronian. The granite cuts across the strike of the Huronian and in places it may have engulfed part of the quartzite, for the latter is completely surrounded by granite. The iron formation in this vicinity is metamorphosed to a magnetite-grunerite rock, and the quartzite is changed to a gneiss.

The granite contains malacon and a little hyacinth. The hyacinths which occur as separate rounded grains and as cores in malacon are thought to be xenocrysts and probably indicate assimilation either of the Huronian rocks or of pre-Huronian granite. If so, the heavy mineral work confirms the field conclusions. A granite about three-quarters of a mile south of the Huronian contact also contains a mixed accessory mineral suite.

Palmer area.—The Huronian formations in the vicinity of Palmer, Michigan, have been intruded extensively by granite. The relation of the sedimentary series to the granite has been described and mapped by Lamey (1935, p. 1137-1162). The Palmer gneiss, previously considered pre-Huronian, consists of metamorphic Mesnard quartzite, Kona dolomite, Wewe slate, and Ajibik quartzite.

The accessory minerals in the dikes cutting the Huronian are malacon, tourmaline, ilmenite, and apatite. The round seedlike malacons are clouded with fine brown inclusions and closely resemble those in the granite south of Beacon. Tourmaline occurs in some of the dikes as prismatic crystals, strongly pleochroic from colorless, pale pinkish-brown or light-brown, to bluish-green. It is similar to the authigenic tourmaline in the Huronian sedimentary rocks. Both accessory minerals therefore suggest Huronian intrusives.

Samples from an area of red granite about 5 miles south of the Palmer gneiss also contain malacon. The age of this granite cannot be determined by field study. It intrudes the granite and granite gneisses and may be pre-Huronian or Huronian. Tourmaline was not noted in the samples of red granite studied.

CRYSTAL FALLS AREA

The Huronian series in the Crystal Falls area (Fig. 3) has been intruded by dikes, bosses, and stocks, which are usually massive even-granular rocks with minor porphyritic varieties. A description of these rocks and their intrusive relations, location, areal extent, and contact metamorphic effects has been given by Clements, Smyth, and Bayley (1899, p. 187-265). The intrusives range in composition from acidic to basic and ultrabasic. The acidic rocks, which are granites cutting the basic intrusives, have caused profound metamorphic effects, transforming the sediments into mica schists, staurolite-mica schists, and garnetiferous

mica schists. Many of the schists contain bluish tourmaline believed to have formed by pneumatolysis.

Clements, Smyth, and Bayley (1899, p. 162) consider these intrusive rocks post-Huronian, Keweenawan, or post-Keweenawan and point out that they have not been involved in the folding which affected the Huronian formations. However, they conclude that the folding is pre-Keweenawan.

The data obtained by Marsden (1933, p. 4-6), from a study of 18 samples of a granite body intrusive into the Upper Huronian slates in secs. 21 and 28, T. 42 N., R. 32 W., shows that this intrusive body is characterized by malacon similar to that found in other Huronian igneous rocks.

GOGEBIC RANGE

The evidence for a Huronian granite on the Gogebic range is not clear. The possibility that the late granite in the Presque Isle area may be Huronian has been discussed in connection with the pre-Huronian granite. The age of the basic dikes and sills which intrude the Middle Huronian in the central part of the Gogebic range has been open to question. Two ages have been suggested—namely, Middle Keweenawan and pre-Keweenawan. A few dikes cut both the Huronian and the Keweenawan, but many do not appear to cut the Keweenawan and therefore may be pre-Keweenawan. A small aplitic dike cutting a large pre-Keweenawan sill in the iron formation near the N¼ corner sec. 17, T. 47 N., R. 44 W., contains malacon which suggests Huronian age.

SUMMARY OF HURONIAN AND RELATED GRANITES

A late granite on the South Shore contains malacon which is distinctly different from the zircon in the still later Keweenawan igneous rocks. This difference suggests that there is no close genetic relationship between these late pre-Cambrian igneous rocks.

In several areas malacon-bearing granite can be conclusively shown by field relations to be post-Upper Huronian, whereas in other areas a malacon-bearing granite is pre-Middle Huronian, and it is probable that some malacon-bearing granites are pre-Huronian, for scattered malacon grains are found in the Lower Huronian sedimentary rocks. Two interpretations are possible: (1) Two distinct periods of granitic intrusion contain malacon. (2) Only one general period of granitic intrusion contains malacon, but this was long and extended through several epochs of igneous activity. The first postulate requires no discussion, for it would simply mean that two periods of intrusion of widely separated age contain the same variety of zircon in the same area. The second postulate requires some explanation. The presence of hyacinth in the

Keewatin flows and in the early pre-Huronian granites suggests a genetic relation between the two rocks. Likewise the Keweenawan igneous rocks may be considered to represent a single but long period of igneous activity, which was initiated by a thick series of lava flows and then intruded by a differentiated gabbro and a later granite. This sequence is characterized by a distinctive variety of zircon in the early as well as late phases. The malacon-bearing rocks may possibly represent a comparable igneous sequence which included at least two epochs of intrusion separated by an epoch (Huronian) of extrusion and sedimentation.

KEWEENAWAN

It has been estimated that in the Lake Superior region during the Keweenawan period about 30,000 feet of flows was extruded and about 20,000 feet of terrestrial shallow-water sediments was deposited. The Keweenawan rocks include three major divisions: (1) the lower sandstones and conglomerates, (2) the middle basic flows, arkoses, and acidic and basic intrusives, and (3) the upper conglomerates, shales, arkoses, and sandstones.

LOWER KEWEENAWAN SEDIMENTS

GENERAL STATEMENT

The Lower Keweenawan sandstone lies stratigraphically below the extrusive member and crops out to the north of the Upper Huronian sediments on the Penokee-Gogebic range. This formation, from 50 to 400 feet thick, is not known to occur in the other areas covered by this work. It is a clean rather firmly cemented sandstone with a well-developed conglomerate at the base. The conglomerate contains slate, vein quartz, quartzite, graywacke, jasper, chert, and mica schist pebbles.

DETRITAL HEAVY MINERALS

Zircon and the opaque minerals are dominant, with biotite, clinozoisite, and apatite in smaller percentages, and rutile, hornblende, chlorite, epidote, sphene, anatase, and tourmaline rare. Biotite, chlorite, epidote, and hornblende occur as irregular grains, whereas anatase, rutile, and sphene are euhedral. Leucoxene and opaque minerals (largely ilmenite) range in shape from angular to round. The characteristics of these minerals do not differ from those of the same minerals in the Huronian.

APATITE: Occurs as rounded grains and crystals, whereas in the Huronian it is irregular or euhedral. The rounded grains are probably detrital, the rounding being produced by abrasion or partial solution. The euhedral grains may be inclusions derived from the quartz by laboratory crushing.

ZIRCON: Dominantly moderately rounded colorless "normal" zircon, described on a later page under the heading Middle Keweenawan Igneous rocks. Elliptically zoned malacon and brownish to purple hyacinth are not abundant. A few colorless

euhedral grains show the first order prism and pyramid with or without the basal pinacoid. The euhedral zircons were probably included within detrital quartz and therefore were not subject to abrasion during transportation.

DETRITAL-INCLUSION HEAVY MINERALS

The following detrital-inclusion heavy minerals were noted: apatite, biotite, epidote, garnet, hornblende, hypersthene, ilmenite, leucoxene, sphene, tourmaline, and zircon. The characteristics of these minerals do not differ greatly from previous descriptions. The "normal" type of zircon is most abundant, with malacon and hyacinth in minor amounts.

The pink garnet in the inclusion suite indicates that the source rocks of the Lower Keweenawan sandstone contained this mineral although it is absent in the detrital suite. Its absence may be due to elimination by abrasion, to sorting during transportation, or to alteration or solution since deposition.

The occurrence of euhedral tourmaline, which closely resembles the authigenic grains in the Huronian, within the quartz grains of the Lower Keweenawan sandstone suggests that the formation of the secondary tourmaline in the Huronian took place prior to the deposition of the Lower Keweenawan.

SOURCE OF LOWER KEWEENAWAN SEDIMENTS

Van Hise and Leith (1911, p. 368) state that the Lower Keweenawan sediments on the Gogebic range were derived from the Huronian and Archean rocks and "really represent the first deposits of the transgressing Keweenawan sea and antedate the igneous epoch of the Keweenawan altogether." The heavy-mineral evidence, however, suggests that some of the Lower Keweenawan sediments were derived mainly from Keweenawan igneous rocks, probably acidic flows. Immediately upon extrusion, the initial Keweenawan flows were subjected to weathering and erosion. The sediments thus derived were in part transported beyond the border of the early flows and deposited with other detritus, forming sandstone that now underlies the Middle Keweenawan extrusives, which spread more widely than the early flows. The evidence for this conclusion is as follows: (1) The detrital zircon in the Lower Keweenawan sediments is predominantly colorless and of the "normal" type. Malacon and hyacinth occur only in minor amounts. (2) A study of the inclusions within the quartz grains of the Lower Keweenawan sediments shows that "normal" zircon is abundant, with malacon and hyacinth in subordinate amounts. (3) Detrital tourmaline is extremely rare in the Lower Keweenawan whereas it is more common in the Huronian sediments. (4) If the Lower Keweenawan sediments were derived largely from the pre-Keweenawan rocks, hyacinth would have become incorporated into the sediments in larger quantities than are found on the Gogebic range.

MIDDLE KEWEENAWAN IGNEOUS ROCKS

GENERAL STATEMENT

The Middle Keweenawan in northern Wisconsin and Michigan consists of a thick series of volcanic rocks with some interbedded sedimentary formations, intruded by a differentiated gabbro and a late granite. Aldrich (1929, p. 230-231, 247) considers the gabbro and granite to be late Middle or perhaps Upper Keweenawan because of their intrusive relations with the Great Conglomerate. The exact age of the intrusive rocks is unknown, for they are not found in contact with the Upper Keweenawan. The intrusive and extrusive rocks are considered to be comagmatic because of their close age relation and intimate field association.

Granite, gabbro, granophyr, rhyolite, anorthosite, and basic flows are included in the Keweenawan igneous sequence. Their petrographic character and distribution have been studied by Irving (1880, p. 167-207; 1883). The areal distribution of the rock types and the locations of the samples examined are shown on Figure 4. The area most intensively studied is near Mellen, Wisconsin, but samples were examined from as far west as R. 5 W. in Wisconsin and as far east as Lake Gogebic in Michigan.

HEAVY ACCESSORY MINERALS

General statement.—The heavy accessory minerals in the Keweenawan igneous rocks are apatite, fluorite, ilmenite, leucoxene, magnetite, sphene, and zircon. With the exception of zircon, they have the same characteristics as those in the older granites so will not be described again. The dominant variety of zircon in the Keweenawan series is referred to throughout the paper as the "normal" type.

"Normal" type zircon.—The zircons usually have a well-developed crystal form with sharp crystal angles. The habit is simple, commonly consisting of a combination of a unit prism and pyramid, the pyramid faces usually making an angle of about 45 degrees with the prism. Some crystals are terminated by a basal pinacoid. A few show both first and second order prisms. The crystals vary somewhat in shape and have dimensional ratios from 10:1 to 1.3:1. The most common form has a dimensional ratio of about 3:1. Many are zoned with the inner zones following the external crystal form, but there are notable deviations. There are numerous acicular, crystalline, and irregular gaseous and opaque inclusions, most of which have a random orientation, but a few show parallelism with a crystallographic direction. Some grains show imperfect growth, and others, slightly rounded, suggest minor resorption of an earlier crystal. Many grains are cracked and broken, possibly by the laboratory crushing. In some grains the fractures seem to be natural,

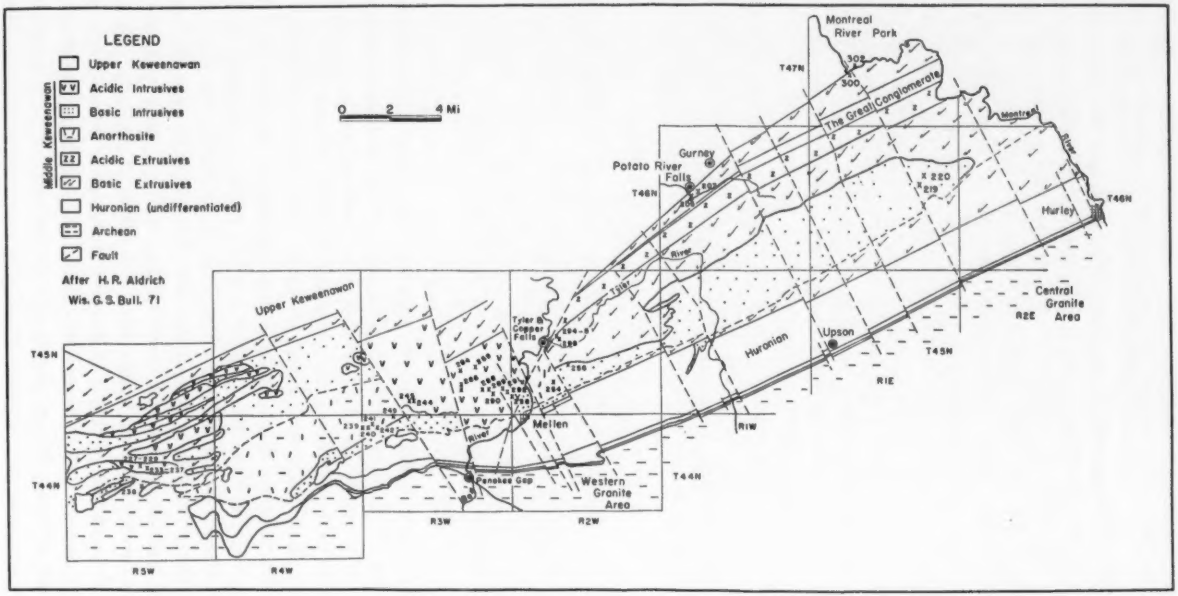

FIGURE 4.—*Map of Mellen area, Wisconsin*

for iron staining extends into the cracks. Most of the zircons are water clear, although some are light tan to yellow. They have strong birefringence and high refringence characteristic of common zircon. The indices of refraction are as follows: $N_o = 1.915 - 1.920$, $N_e = 1.950 - 1.955$,

TABLE 5.—*Relative percentage of heavy and accessory minerals*
In Keweenawan igneous rocks near Mellen, Wisconsin

	Heavy minerals						Accessory minerals					
	Sample no.	Hornblende	Biotite	Chlorite	Epidote	Accessory minerals	Zircon	Apatite	Fluorite	Sphene	Ilmenite	Leucoxene
Granophr, Mellen Wisconsin	227	1	.....	4	x	95	6	3	.....	9	43	39
	228	.....	1	13	.....	86	7	5	.....	.....	50	38
	233	65	x	3	7	25	32	12	.....	.....	56	.....
	234	2	.....	24	20	54	12	5	.....	.....	82	1
	235	1	.....	32	10	57	29	7	.....	.....	64	.....
Granite, Mellen Wisconsin	244	86	2	.....	.....	12	42	1	9	.....	48	.....
	245	92	2	.....	.....	6	34	5	8	.....	53	.....
	247	32	61	.....	.....	7	30	5	25	30	10	.....
	258	52	23	1	2	22	19	5	.....	.....	76	.....
	259	46	45	1	.....	8	19	14	4	38	25	.....
	286	39	52	.....	.....	9	20	25	x	30	25	.....
	288	46	45	x	.....	9	11	24	4	38	23	.....
	290	70	25	.....	2	3	19	20	.....	3	58	.....
	291	90	8	.....	1	1	1	28	x	.....	71	.....
	292	83	7	.....	.....	10	31	5	.....	.....	64	.....

$N_o - N_e = .040$. The index varies to some extent from grain to grain with an observed difference of about .005.

Slight changes have been noted in the varietal characteristics of the zircons in the Keweenawan series, such as varying proportions of zoned crystals or differences in the kind or abundance of inclusions, but no important change in crystal habit has been recognized. It has been impossible, with one exception, to relate the observed changes in the varietal characteristics of the zircon to the rock type or particular mode of formation. The only variety which can be definitely related to a rock type is the zircon found in the granophyr.

Zircon in granophyr.—An unusual variety of zircon, associated with a minor percentage of the "normal" type, occurs in four of the ten samples of the granophyr (a granitic differentiate of basic intrusives) studied. This variety has a corroded appearance with jagged, serrated edges and a pitted, striated, and irregular surface. The grains have an irregular outline often vaguely suggesting prismatic form. They are usually cloudy

and brownish but are occasionally colorless; the cloudy brown color is caused by numerous brown dustlike inclusions.

This variety is thought to be due to partial resorption of earlier formed crystals, resulting in the irregular serrated grains. Some retain a portion of the crystal form characteristic of the "normal" zircon—a part of the grain may be irregular, and the other part may show the normal crystal habit. This probably resulted from the partial inclusion of the crystal in some other mineral which protected it from resorption. This variety seems to indicate a particular environment of development which must be closely related to formation of the granophyr.

Accessory minerals of Keweenawan granite and other granites of region.—In the Mellen area granites of two ages crop out within 4 miles of each other—the Keweenawan granite north of Mellen and the pre-Huronian granite south of Penokee gap. This affords an excellent opportunity to observe and compare the accessory mineral suites of two granites within a limited area. If there is an overlapping of the accessory mineral suite or the varietal characteristics of the minerals, it might be expected in an area where the granites are closely associated. The pre-Huronian granite has been called "Laurentian" or "Archean" by Irving (1880, p. 92-96) and Van Hise and Leith (1911, p. 226). Although the rock directly beneath the Huronian series is pre-Huronian, the age of the rock a short distance south of the contact is unknown. Lithologically the rock varies from a gneiss to massive pink orthoclase granite. From the field relations it is evident that there are granites of more than one age, but it has been impossible, except locally, to determine their respective ages. The gneissic granites appear to be the older and are intruded by a later pink granite. Locally the pink granite is lithologically similar to the Keweenawan granite.

A study of the accessory minerals of the granites indicates a complex history; one granite contains hyacinth, the second malacon, and the third "normal" zircon. From limited field evidence the granites appear to be associated in the order of intrusion indicated by the accessory minerals. Granite containing malacon cuts the older gneissic granite which contains hyacinth. The relationship between the granite containing the "normal" zircons and that containing chiefly malacon has not been determined in the field. The samples which contain the "normal" zircons yield the same accessory mineral suite as the Keweenawan granite 4 miles north of the Penokee Gap area. The occurrence of the Keweenawan granite within the igneous complex might be anticipated, but even in this area it has not been possible to identify it by field methods. This area illustrates the individuality of the zircon, even though the three granites are

in close association. In all cases the identification of the various granites based upon the variety of zircon is definite.

If the relative percentages of the accessory minerals alone were considered it would be impossible to recognize and distinguish the various granites, for the percentages of the accessory minerals in the three granites overlap. There is a greater difference in the relative percentage of the accessory minerals within the Keweenawan granite than among the samples of the several intrusives in the igneous complex south of Penokee Gap. This area shows the similarity in the relative percentages of the accessory minerals within a rock type, indicating that a correlation based on the relative percentages is unreliable. It is a correlation of rock type and not a correlation of age or a criterion of genetic relationship.

MIDDLE KEWEENAWAN SEDIMENTS

GENERAL STATEMENT

Lenses of conglomerate, arkose, and sandstone are interbedded with the Middle Keweenawan basic flows. These sediments were derived mainly from the erosion of felsite and porphyry flows, as is shown by the felsite and porphyry pebbles and granules. The acidic flows probably formed the higher elevations and consequently were subjected to more severe erosion than the basic flows and thus furnished the larger part of the sediments.

DETRITAL HEAVY MINERALS

These sediments are characterized by the great abundance of opaque heavy minerals and by zircon exclusively of the "normal" type. Leucoxene and apatite occur in minor quantities. In one sample the opaque material (largely ilmenite) constitutes 16 per cent of the arkose by weight and 98 per cent of the heavy minerals by count (Table 6). Heavy mineral grains are but slightly rounded and sorted, thus indicating a near-by source, probably the acidic flows.

UPPER KEWEENAWAN SEDIMENTS

GENERAL STATEMENT

The Upper Keweenawan of northern Michigan and Wisconsin consists of a thick series of conglomerate, arkoses, sandstones, and shales. Thwaites (1912) has studied this series in northern Wisconsin and gives the following section.

Bayfield group

Chequamegon sandstone	Feet
Red and white sandstone composed predominantly of quartz grains, with thin lenticular beds of sandy shale	1,000

TABLE 6.—*Heavy minerals in the Keweenawan sedimentary formations*

On the south shore of Lake Superior

	Sample no.	Weight per cent	Relative per cent													
			Zircon	Tourmaline	Apatite	Rutile	Leucoxene	Ilmenite	Hornblende	Chlorite	Biotite	Epidote	Garnet	Sphene	Anatase	Staurolite
Keweenawan or Cambrian sandstone, Felch district	191	.006	64	13	...	...	7	13	2	...	...	...	...	...	1	...
	192	.007	5	3	1	x	4	53	32	...	...	x	...	...	2	...
	193	6.4	x	..	..	..	..	100	..	..	..	..	..	..	..	..
	197	.008	27	12	..	...	27	34	x	...	...	...	...	...	...	...
	436	.06	49	4	x	...	26	21	x	...	...	...	...	...	...	...
Jacobsville sandstone																
Burns landing	148	1.82	4	1	7	...	4	80	...	...	x	...	4	...	x	...
Marquette	149	.79	1	2	5	...	2	89	...	...	...	...	1	...	x	...
L'Anse	530	.....	5	2	1	x	9	80	...	...	...	...	3	...	x	...
Sherman hill	531	.....	2	x	3	...	3	88	...	...	...	...	4	...	...	...
Chequamegon sandstone	440	.59	11	3	...	x	17	68	...	...	...	...	...	...	1	...
Bayfield	439	.74	7	2	x	...	11	80	...	...	...	...	...	...	...	...
	438	.56	8	5	.....		20	67	...	...	...	...	...	...	x	...
	437	.39	4	1	.....		10	85	...	...	...	...	...	...	...	...
Devil's Island sandstone	448	.04	16	10	...	x	9	64	...	...	...	...	x	...	1	...
Cornucopia	447	.04	26	8	...	x	13	53	...	...	...	...	...	...	x	...
	446	.03	21	4	...	1	11	63	...	...	...	...	...	...	x	...
	445	.03	17	12	...	x	9	60	...	...	...	...	x	...	2	...
	444	.03	19	20	...	...	21	38	...	...	...	...	...	...	2	...
	443	.04	18	16	...	...	15	50	x	...	...	...	...	...	1	...
	442	.12	13	8	...	x	24	55	...	...	...	...	...	...	...	...
	441	.02	27	16	...	1	36	20	...	...	...	...	...	...	x	...
Orienta sandstone	454	.71	5	3	4	x	30	58	...	...	...	...	...	...	x	...
Falls on Iron River	453	.39	5	1	3	...	19	72	...	...	...	...	...	...	...	...
	452	.66	6	x	7	1	30	55	...	...	...	...	...	...	1	...
	451	.55	3	2	3	...	21	71	...	...	...	...	...	...	...	...
	450	1.03	7	2	3	x	32	54	...	...	...	...	...	...	2	...
	449	.52	6	3	5	...	22	62	...	...	...	...	...	...	2	...
Middle River	11245	.....	2	1	5	...	4	88	...	...	...	...	...	...	...	...
	11241	.....	2	x	3	...	7	88	...	...	...	...	x	...	...	...
	11240	.....	2	1	3	...	5	89	...	...	...	...	x	...	...	...
	11239	.....	2	1	5	...	5	87	...	...	...	...	x	...	...	...
	11237	.....	1	1	4	...	3	91	...	...	...	...	x	...	...	...
	11236	.....	2	x	x	...	5	92	x	...	...	...	1	...	...	...
	11235	.....	x	1	3	...	6	87	...	...	...	...	3	...	...	...
	11234	.....	1	x	3	...	4	87	...	...	...	...	5	...	...	...
	11233	.....	2	...	2	...	3	90	...	...	...	...	3	...	...	...
Eileen sandstone	425	1.8	2	x	5	x	4	87	...	...	...	...	2	...	x	...
Fish Creek	424	3.5	3	x	5	x	4	87	...	...	...	...	1	...	...	...
	423	1.1	2	3	5	...	5	78	...	...	...	...	7	...	x	...
	422	.4	4	x	3	...	4	82	...	...	...	...	7	...	...	...
	421	1.9	3	x	5	...	6	79	...	...	...	...	7	...	x	...
	420	1.4	2	1	8	...	6	79	...	...	...	...	4	...	x	...
	419	1.3	3	x	4	...	8	79	...	...	...	...	5	...	1	...
	418	1.4	3	1	4	...	8	75	...	...	x	...	5	...	4	...
Eileen sandstone	11336	.....	1	1	4	...	1	93	...	...	...	...	x	...	...	...
St. Louis River	11324	.....	x	2	4	...	4	89	...	...	...	...	1	...	...	...
	11289	.....	6	x	6	...	68	11	3	...	...	...	6	...	...	...
	11299	.....	14	3	12	...	21	46	...	...	...	...	4	...	...	...

x less than 1 per cent.

TABLE 6.—*Heavy minerals in the Keweenawan sedimentary formations*—Continued

On the south shore of Lake Superior

	Sample no.	Weight per cent	Relative per cent													
			Zircon	Tourmaline	Apatite	Rutile	Leucoxene	Ilmenite	Hornblende	Chlorite	Biotite	Epidote	Garnet	Sphene	Anatase	Staurolite
Amnicon sandstone Middle River	11232	.....	x	1	6	...	4	76	...	...	...	6	6	...	1	...
	11229	.....	3	...	2	x	3	69	...	...	...	20	3	...	...	...
	1234R	.....	2	x	2	...	5	50	x	1	...	38	2	...	...	...
Clinton Point	11121	.....	1	x	1	...	3	76	...	...	...	8	11	...	...	...
	11122	.....	6	1	5	1	14	46	x	x	...	16	11	...	...	...
	11127	.....	1	1	1	...	5	19	...	...	...	63	10	...	...	x
	11128	.....	1	1	2	...	2	52	x	...	...	35	5	...	...	2
	11131	.....	x	x	2	...	1	56	...	x	...	39	2	...	...	...
	11132	.....	3	x	3	...	2	42	x	...	1	47	2	...	...	x
	11133	.....	3	1	2	x	5	16	...	...	...	65	8	...	...	x
	11136	.....	2	1	2	...	4	37	...	...	...	49	5	...	...	...
	11137	.....	x	x	1	x	x	40	...	...	...	47	12	...	...	x
	11139	.....	x	x	4	...	2	58	...	...	...	34	2	...	...	...
Bad River White River	11411	.....	4	1	12	x	15	48	...	...	...	7	13	...	...	...
	11389	.....	1	x	1	...	1	80	...	...	...	16	1	...	...	...
Fish Creek	430	3.6	4	x	1	...	5	50	...	...	...	39	1	...	...	x
	429	4.4	x	x	x	...	5	44	...	...	...	51	x	...	...	x
	427	2.5	3	x	x	...	4	48	...	...	...	44	x	...	...	1
	426	3.1	1	1	...	...	5	46	...	...	...	46	1	x	...	x
Freda sandstone Potato River Falls	436	21.2	2	x	x	...	x	87	...	...	...	11	x	...	...	...
Montreal River Park	415	4.5	9	x	3	...	7	37	...	...	...	40	4	...	...	...
	414	1.5	5	x	1	x	6	45	...	...	...	30	13	...	...	...
	413	1.8	4	1	3	...	5	51	...	...	...	33	3	...	...	...
	412	3.2	2	x	3	x	6	57	...	...	...	30	2	...	...	...
	411	2.9	3	x	3	...	2	54	...	...	...	35	3	...	...	...
	410	1.7	3	x	2	...	x	63	...	...	...	30	2	...	...	...
	409	1.4	3	x	1	x	3	42	...	...	...	45	6	...	...	x
Tyler Falls	408	3.1	1	x	1	...	1	78	...	...	...	18	1	...	...	...
	407	18.6	x	...	1	...	6	73	...	...	...	19	1	...	...	...
	406	17.0	x	...	1	...	4	82	...	...	...	13	x	...	...	...
	405	16.4	1	x	x	...	8	84	...	...	...	6	1	...	...	...
	404	10.8	x	...	x	...	...	88	...	...	...	12	x	...	...	...
	403	9.3	1	...	x	...	...	80	...	...	...	18	1	...	...	...
	402	11.7	2	x	1	...	...	86	...	...	...	11	x	...	...	...
	401	7.5	7	x	5	...	3	58	...	...	...	27	...	x	...	...
Nonesuch shale Potato River Falls	435	6.0	2	x	1	...	2	60	...	1	...	34	x	...	...	...
	434	3.4	7	x	x	...	x	58	...	2	...	33	x	...	...	...
	433	13.6	1	x	x	...	3	61	...	x	...	34	1	...	...	x
	432	.4	7	x	x	...	1	40	...	2	...	50	x	...	...	...
	431	7.5	2	...	x	...	4	54	...	1	...	37	2	...	...	...
Outer conglomerate Montreal River	416	14.5	x	...	1	...	1	86	...	...	...	12	...	...	...	...
Middle Keweenawan arkose Montreal River	417	16.1	x	...	x	...	2	98	...	...	...	...	...	...	...	...

x less than 1 per cent.

TABLE 6.—*Heavy minerals in the Keweenawan sedimentary formations*—Continued

On the south shore of Lake Superior

	Sample no.	Weight per cent	Relative per cent													
			Zircon	Tourmaline	Apatite	Rutile	Leucoxene	Ilmenite	Hornblende	Chlorite	Biotite	Epidote	Garnet	Sphene	Anatase	Staurolite
Lower Keweenawan sandstone Upson	394	.70	11	...	3	x	4	74	...	x	1	7	...	...	...	...
	395	.76	3	...	2	1	3	78	...	...	9	4	...	x	...	...
	396	.30	8	...	6	...	8	67	...	...	2	9	...	...	...	...
	397	.....	16	...	15	...	54	4	x	9	1	1	...	...	...	...
	398	.50	8	...	5	...	10	14	...	...	61	2	...	...	...	...
	399	.44	12	...	4	...	9	9	...	...	64	2	...	...	...	...
	400	.14	22	...	5	...	30	22	...	...	21	x	...	...	...	...
Copps mine	211	.77	4	...	7	x	3	79	...	...	x	7	...	...	...	...
Sunday Lake mine	281	.34	50	...	...	1	44	5	x	...	...	...	...	...	x	...
Wakefield	282	.17	34	...	2	x	23	41	...	...	...	...	...	x	...	...
	283	1.2	17	x	8	...	7	60	...	8	...	x	...	...	...	...

x less than 1 per cent.

	Feet
Devil's Island sandstone	
Pink and white pure quartz sandstone with abundant ripple marks	300
Orienta sandstone	
Like Chequamegon in its upper part, but containing more feldspar grains especially near the base	3,000
Oronto group	
Amnicon formation	
Red and greenish shales, arkose, sandstone, and conglomerate	5,000
Eileen sandstone	
Red and white arkose and sandstone	2,000
Freda sandstone	
Fine-grained red and greenish arkosic sandstone with some conglomerate at top and bottom	12,000
Nonesuch shale	
Black, gray, and red arkose and shale	350
Outer conglomerate	
Coarse conglomerate and arkose	1,200
Total	24,850

DETRITAL HEAVY MINERALS

More than 100 samples of Upper Keweenawan sediments were examined, and the following heavy minerals were identified.

ANATASE: Yellow tabular euhedral grains. Zoning is occasionally well developed, and the crystals are commonly filled with opaque dustlike inclusions.

APATITE: Subangular to well-rounded grains and as euhedral crystals in the Oronto group. The crystals probably are inclusions which have been broken out during crushing. Inasmuch as the Bayfield sandstone is weakly cemented, breaking the rock to grain size did not free many of the apatite inclusions. All the apatite in the Bayfield group is well rounded. The grains are generally free of inclusions.

BIOTITE: Brown to yellowish-green rounded to irregular cleavage fragments.

CHLORITE: Rounded to irregular green cleavage fragments.

EPIDOTE: Angular to subangular light yellowish-green grains commonly clouded with alteration products or inclusions. Clear grains are not abundant. Zoisite and clinozoisite appear but are included with epidote because of the difficulty in distinguishing these minerals.

FLUORITE: Grains are clear, colorless, and subangular to well rounded.

GARNET: Most are clear and colorless, although there are a few pink grains. The grains are subangular to angular and generally only very slightly etched. Some are clouded with fine dustlike inclusions.

HORNBLENDE: Green to brownish-green, elongated and sometimes slightly rounded cleavage fragments. The grains are pleochroic from green to yellowish-green.

ILMENITE: Although many of the black opaque grains undoubtedly are this mineral, other opaque moderately magnetic minerals have been included here. Some martite is present, but no satisfactory method was found to distinguish it rapidly. Much of the ilmenite shows partial alteration to leucoxene. The surfaces of the grains are generally pitted and rough, and their shape ranges from angular through subangular to round. The rounded grains are more common in the Bayfield, whereas the subangular and angular grains are most abundant in the Oronto. Magnetite was previously reported to be very abundant in the Keweenawan sediments, but the present work indicates that the abundant black opaque mineral is ilmenite rather than magnetite.

LEUCOXENE: Porous white to yellowish-brown grains are characteristically angular in the Oronto group and subangular to well-rounded in the Bayfield group. The ilmenite in the Oronto group has been partially altered to leucoxene *in situ*, whereas the leucoxene of the Bayfield is largely detrital.

RUTILE: Common as reddish-brown prismatic crystals, although rounded grains occur.

SPHENE: Occurs as yellow crystals, which show no evidence of rounding. It is probable that they occur as inclusions within quartz and feldspar and were broken out during crushing.

STAUROLITE: Straw-yellow angular grains contain abundant colorless and opaque inclusions.

TOURMALINE: Ranges from brown to green and blue. The brown variety is the most common. The larger grains are rather well rounded, whereas the smaller grains are generally prismatic with rounded terminations. Some contain small colorless and opaque inclusions. The surface of the grains is generally etched.

ZIRCON: The zircon of the Keweenawan sediments is of three general types: (1) "normal," (2) malacon, and (3) hyacinth. The "normal" zircon predominates, malacon is common, and the hyacinth is rather rare. Iron oxide commonly stains the surface of the grains a yellowish brown, making it difficult to ascertain the true color of the grain. Prismatic grains with rounded terminations are most abundant. Spherical to ovoid-shaped grains are common in the Devil's Island sandstone but are otherwise rare. Zoning is rather common but is indistinguishable if the grains are frosted or coated with iron oxide. Some grains have irregular, opaque and colorless inclusions and others are cloudy with dust.

Table 6 gives the relative percentages of the heavy minerals as determined by count in the various Upper Keweenawan formations.

ORONTO GROUP

GENERAL STATEMENT

The Oronto group consists of several thousand feet of poorly sorted, slightly weathered detritus. The material was largely derived from the Keweenawan flows, as is indicated by the numerous pebbles, and transported only a short distance to the site of deposition. It is probable that the slow downwarping of the Lake Superior geosyncline caused the rapid erosion of the borders of the basin and concurrently the deposition of sediments down the dip as alluvial fans. Evidence suggesting continental deposition of the Oronto group is as follows: (1) rapid changes in lithology, (2) abundant and irregular cross lamination, (3) mud cracks and rain prints, (4) poor sorting, (5) angular grains, (6) lithologic units thin rapidly along strike, and (7) channels in shale beds filled with sandstone.

OUTER CONGLOMERATE

The Outer conglomerate, the basal deposit of this sequence, is composed of pebbles and boulders as much as 15 inches or more in diameter, with an arkosic matrix. The pebbles are dominantly basalt, diabase, gabbro, and felsite, with subordinate amounts of quartzite, iron formation, chert, slate, vein quartz, and granite. The sizes of the pebbles indicate that the gradients of the streams must have been steep. The quartzite, iron formation, and slate pebbles indicate erosion of the Huronian formations south of the area under discussion. Arkose is interbedded with the conglomerate.

The arkose beds in the Outer conglomerate contain abundant opaque minerals (largely ilmenite), with epidote second in importance. The heavy minerals make up about 14 per cent of the arkose by weight, and 86 per cent of this by count consists of opaque minerals. Leucoxene, apatite, and zircon occur in small percentages (Table 6). The zircon is dominantly the clear colorless "normal" type. The heavy mineral suite of the arkosic beds is very similar to that of the arkose interbedded with the Middle Keweenawan flows, the main difference being that the Outer conglomerate contains an appreciable percentage of epidote probably indicating that the basic flows were contributing sediments in important quantities.

NONESUCH SHALE

The Nonesuch shale lies stratigraphically above and is continuous with the Outer conglomerate. The rock is a red, gray, or black arkose and gray shale. The formation is remarkably uniform in lithology and thickness. Ripple marks and mud cracks are numerous, indicating a shallow-water origin for the deposit. The basic character of the formation sug-

gests that the detritus was largely derived from the basic Keweenawan lava flows.

Samples of Nonesuch shale were collected from the section exposed on the Potato River, where it is dominantly shale with some interbedded arkose. The heavy minerals are epidote, chlorite, garnet, ilmenite, leucoxene, staurolite, tourmaline, and zircon. The suite is characterized by the abundance of ilmenite, epidote, and garnet (Table 6). The heavy mineral grains are small and very angular. Apatite crystals are common. The zircon is dominantly of the "normal" type, with malacon rather common and hyacinth rare. The heavy minerals range from .4 per cent to about 14 per cent by weight.

FREDA SANDSTONE

The Freda sandstone, a coarse to fine poorly sorted red to greenish-gray arkose with interbedded lenses of red and green micaceous shale, is composed dominantly of feldspars and fragments of acidic and basic flows, with quartz averaging less than 25 per cent of the rock.

The Freda sandstone was sampled on the Potato River, from the Montreal River Park section and from the Tyler Falls section. The heavy mineral suite is composed of apatite, epidote, garnet, ilmenite, leucoxene, rutile, sphene, staurolite, and zircon. The suite is characterized by the abundance of ilmenite and epidote and by the garnet (Table 6). The larger grains, especially apatite, tourmaline, and zircon, are somewhat rounded, whereas the smaller grains and the epidote, ilmenite, and leucoxene are angular to subangular. The percentage of heavy minerals by weight varies from 1.4 to 21.2 per cent of the arkose. The heavy mineral suite of the Freda sandstone and shales is the same as that of the Nonesuch shale, there being as much variety within either as between the two formations. The shale beds of the Freda can be distinguished from the coarser arkosic phases of the same formation only on the basis of grain size.

EILEEN SANDSTONE

On the south fork of Fish Creek, in secs. 20 and 21, T. 47 N., R. 5 W., 1800 feet of arkosic sandstone is exposed. This is the section which Thwaites made the type of the Eileen formation. The rock is a red to white mottled somewhat shaly, arkosic sandstone. One-third to half the rock is composed of quartz; the remainder is largely feldspar.

Samples of the Eileen were collected at the type locality. The heavy minerals are anatase, apatite, garnet, ilmenite, leucoxene, tourmaline, zircon, and in one sample a little biotite and rutile. The major differences between the Freda and the Eileen are that the Eileen does not contain epidote, an important constituent of the Freda, and that the heavy min-

eral grains of the Eileen show more rounding than those of the Freda. The percentage of heavy minerals by weight in the Eileen ranges from .4 to 3.5 per cent (Table 6).

AMNICON FORMATION

The Amnicon formation is a greenish and red coarse locally conglomeratic arkose with interbedded red shales. The Amnicon on Fish Creek and on Middle River very closely resembles the Freda sandstone lithologically.

Samples of Amnicon were collected from the section exposed on Fish Creek, Bayfield County, Wisconsin. The heavy minerals are apatite, epidote, garnet, ilmenite, leucoxene, sphene, staurolite, tourmaline, and zircon. The heavy mineral grains are the same in general percentages, appearance, characteristics, and varieties as those of the Freda sandstone. The percentage of heavy minerals by weight in the Amnicon ranges from 2.5 to 4.4 per cent.

SUMMARY AND DISCUSSION OF HEAVY MINERALS OF ORONTO GROUP

The four formations—Outer conglomerate, Nonesuch shale, Freda sandstone, and the Amnicon formation—have the same heavy minerals: anatase, apatite, biotite, chlorite, epidote, fluorite, garnet, hornblende, ilmenite, leucoxene, sphene, rutile, staurolite, tourmaline, zircon, and zoisite. The suites of these formations are so similar that one formation cannot be distinguished from another on a heavy mineral basis. The Eileen sandstone differs in two important respects from the other formations of the Oronto group: (1) Epidote is absent in the Eileen; and (2) the heavy mineral grains of the Eileen are much rounder than those in the other formations of the Oronto group. In all other respects the Eileen is identical with the other sediments of the Oronto group. The heavy minerals of the Oronto series (excluding the Eileen) range from .4 to 21 per cent and average 7.4 per cent by weight of the total sample. The following factors probably are responsible for the high average content of the heavy minerals: (1) source rocks contained a large amount of heavy minerals, (2) short transportation, (3) incomplete weathering, and (4) concentration of heavy minerals by current and wave action.

STRATIGRAPHIC PROBLEMS

The Eileen sandstone has a striking lithological and heavy mineral similarity to the formations of the Bayfield group. These facts have led to a re-examination of the correlation of the Eileen on the basis of lithology, structure, and heavy minerals.

The type locality of the Eileen sandstone is located on the south fork of Fish Creek in sec. 20 and 21, T. 47 N., R. 5 W., in the town of Eileen, Bayfield County, Wisconsin (Fig. 5A). Eighteen hundred feet of mottled

red and white arkosic (about one-third quartz) vertically dipping sandstone is exposed here. The heavy mineral analyses of the Eileen sandstone as given in Table 6 were obtained from samples collected at this locality.

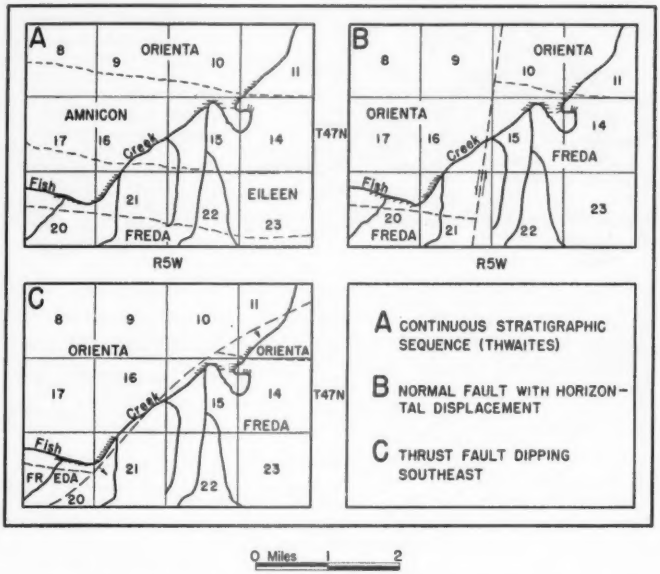

FIGURE 5.—*Structural interpretations of the outcrops on Fish Creek, Wisconsin*

Thwaites assumed that the Eileen sandstone lay below the Amnicon sandstone on the basis of the distribution of outcrops and the strikes and dips as shown in Figure 5A. As may be noted in this figure the Eileen at the type locality is not in contact with any other formation of the Oronto series but is separated by an unexposed interval of almost 1½ miles from the Amnicon formation in secs. 14 and 15, T. 47 N., R. 5 W. Therefore the relation of the Eileen to the Amnicon is not definitely known at the type locality, and the sequence postulated by Thwaites is only one of several possible explanations of the relation of these two sandstones. Figure 5C explains the distribution of the outcrop on the basis of a thrust fault, and Figure 5B on the basis of a normal fault. Thwaites (1935, p. 225) suggests that the Douglas thrust fault (fault plane dips to the south) extends into this area. The writers believe that

either the Douglas thrust or an associated minor fault may have caused a displacement of the Orienta and Freda sandstone at this locality. Thwaites (1912, p. 54-55) states that "were it not for the structural relations [Figure 5A] these rocks [the Eileen] might be regarded as the

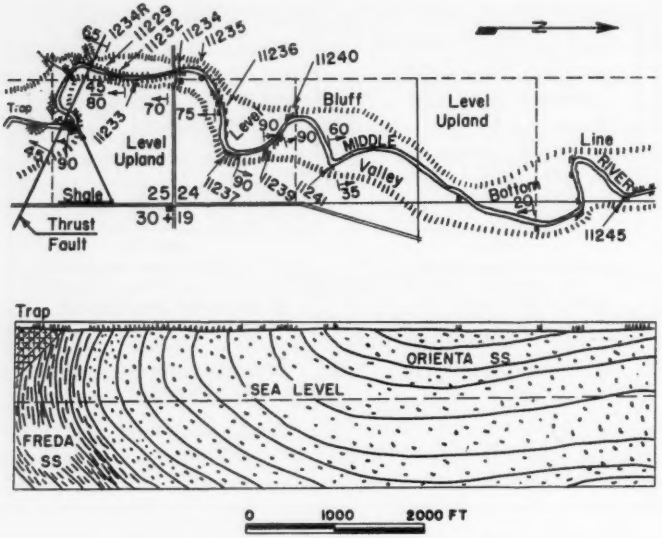

FIGURE 6.—*Outcrop map and structure section*
On Middle River, Douglas County, Wisconsin.

lower part of the Orienta formation". Thwaites realized that lithologically the Eileen is very similar to what he called lower Orienta.

Stratigraphically above the Amnicon in secs. 11, 14, and 15, T. 45 N., R. 5 W., on the south fork of Fish Creek, more than 1000 feet of red and white mottled arkosic (about one-third quartz) vertically dipping sandstone is exposed. This sandstone, called lower Orienta by Thwaites, is similar lithologically to the Eileen at the type locality.

On Middle River, in the eastern part of Douglas County, Wisconsin, more than 3000 feet of Keweenawan sandstone is exposed in a fold on the north side of the Douglas fault (Fig. 6). The lower 365 feet exposed consists of the shaly and arkosic Amnicon formation. The heavy minerals in these beds are the same as those of the Amnicon on Fish Creek. Above the Amnicon on Middle River there is at least 1500 feet of red and white mottled arkosic (about one-third quartz) steeply dipping sand-

stone. This has been described as lower Orienta by Thwaites; on the basis of lithology and heavy minerals, however, it is the same as the Eileen sandstone at the type locality. Above this horizon on Middle River is several hundred feet of typical Orienta sandstone.

The 1300 feet of arkose exposed on the west side of Clinton Point has been mapped as Eileen by Thwaites, although he states (1912, p. 55)

Revised sequence of Upper Keweenawan

	Feet
Bayfield group	
Chequamegon sandstone	1000
Devil's Island sandstone	300
Orienta sandstone	3000
Oronto group	
Freda sandstone	12,000
Nonesuch shale	350
Outer conglomerate	1200
Total	17,850

that it is "not greatly different from the rocks exposed on Bad River", which he assigns to the Amnicon formation. The rock exposed on Clinton Point is a fine-grained shaly red and white mottled arkose, which lithologically resembles the Amnicon formation. The heavy minerals are the same as the suite of the Amnicon formation.

The Amnicon from the Bad River and the Freda from the White River, lithologically and on the heavy mineral basis, belong to the Oronto group as is correctly stated by Thwaites.

The lithological and heavy mineral evidence, with the lack of evidence to the contrary at the type locality on Fish Creek, suggests that the Eileen sandstone belongs above the Amnicon and includes the beds on the Middle River and Fish Creek sections which Thwaites classes as lower Orienta. The Eileen sandstone, which resembles the Bayfield group of sandstones, is probably basal Orienta, and the Amnicon arkose is upper Freda.

The thickness of the Amnicon as given by Thwaites—5000 feet—is included in his estimate of the thickness of the Freda, and the 2000 feet assigned to the Eileen is included in the Orienta. Therefore 7000 feet of sediments is eliminated from the 24,850 feet estimated by Thwaites as the thickness of the Upper Keweenawan sediments, giving a revised estimate of 17,850 feet. The thickness may be much less if the dip of the beds should prove to be lower than estimated or if duplication is discovered.

The red and white mottled arkosic conglomeratic and shaly sandstone exposed on the St. Louis River in eastern Minnesota grades upward into the Orienta sandstone. This basal arkose was correlated as Amnicon by Thwaites, but the lithology, stratigraphic position, and the heavy minerals indicate that it is more likely lower Orienta.

BAYFIELD GROUP

GENERAL STATEMENT

The Bayfield group consists of about 4000 feet of red and white quartz sandstone which has been subdivided by Thwaites into the Chequamegon, the Devil's Island, and the Orienta sandstones.

ORIENTA SANDSTONE

The Orienta sandstone underlies the northwestern part of the Bayfield peninsula and the plain to the west, north of the Douglas fault. The upper part of the Orienta resembles the Chequamegon closely, but the lower Orienta is more feldspathic and more shaly.

The following heavy minerals occur in the Orienta sandstone: anatase, apatite, garnet, ilmenite, leucoxene, rutile, tourmaline, and zircon. The heavy minerals range from .39 to 1.03 per cent of the samples by weight. The zircon of the Orienta is dominantly of the "normal" type, with only small amounts of hyacinth and malacon present. The contact of the Freda (Amnicon of Thwaites) and the Orienta (Eileen and lower Orienta of Thwaites) on Middle River is marked by the rather sudden disappearance of epidote, which is both abundant in and characteristic of the Freda. Garnet, which occurs in the Freda, is in about the same percentage in the feldspathic basal Orienta and gradually disappears upward in the formation (Table 6).

DEVIL'S ISLAND SANDSTONE

According to Thwaites, the Devil's Island sandstone conformably overlies the Orienta. It crops out occasionally along a narrow belt for 25 miles southwest of the type exposures on Devil's Island. This sandstone is characterized by subangular to well-rounded medium-sized quartz grains, thin bedding, and is pink to white. The samples examined were collected at the falls of the Siskowit River at Cornucopia, Bayfield County, Wisconsin.

Ilmenite, leucoxene, tourmaline, and zircon are dominant, and anatase, garnet, hornblende, and rutile occur in minor amounts. The Devil's Island sandstone is characterized by rounder heavy mineral grains and by a greater abundance of tourmaline and zircon than is found in any other Keweenawan sandstone, arkose, or shale. The three samples of the Devil's Island reported by Tyler (1936, p. 55-84) from the type locality show an even greater dominance of tourmaline and zircon. The samples examined from the Cornucopia section seem to be intermediate in heavy mineral composition between the Devil's Island at the type locality and the suite of the overlying Chequamegon sandstone (Table 6). The "normal" type zircon is characteristic of the Devil's Island, although

small percentages of hyacinth and malacon are present. This formation contains only .02 to .12 per cent heavy minerals by weight, the smallest of all the Keweenawan formations examined.

CHEQUAMEGON SANDSTONE

The brown quartzose Chequamegon sandstone, the youngest formation of the Bayfield group, occurs as the surface rock of the central and eastern part of the Bayfield Peninsula as well as the Apostle Islands.

The heavy mineral suite of the Chequamegon sandstone appears to be identical with that of the Orienta sandstone. Ilmenite and leucoxene are dominant, with anatase, apatite, rutile, tourmaline, and zircon in minor quantities (Table 6). The degree of rounding is about the same as in the Orienta. The heavy minerals range from .39 to .74 per cent by weight.

SOURCE OF BAYFIELD SEDIMENTS

The abundance of the "normal" zircons in the Bayfield sediments indicates clearly that they were derived largely from pre-existing Keweenawan sediments or igneous rocks. The minor amount of malacon and hyacinth suggests that the older rocks were not an important source. The quartzose character of the Bayfield indicates that these sediments were subjected to more mature weathering than those of the Oronto group and that the Bayfield group may have been derived from previously existing sediments. The most likely sedimentary source for the Bayfield would be the older Oronto series. Their derivation from this source, however, would necessitate the almost complete elimination of feldspar, epidote, and garnet of the Oronto sediments and a large decrease in the quantity of ilmenite. It seems more likely that the Bayfield sediments were derived from Keweenawan sediments or acidic igneous rocks which did not originally contain large amounts of epidote and ilmenite and that the region from which the garnet was derived during Oronto time had ceased to contribute sediments to this basin of deposition during Bayfield time.

JACOBSVILLE SANDSTONE

The Jacobsville or Eastern sandstone underlies the area southeast of the Keweenawan fault and north of the south trap range in Michigan. This sandstone crops out in a narrow band from L'Anse along the shore to Marquette and extends as far east as Munising where it underlies the Cambrian. Irving (1883, p. 366), Thwaites (1912, p. 102-105), and others believe that the Jacobsville sandstone is the eastern equivalent of the Bayfield group.

The heavy minerals are anatase, apatite, biotite, garnet, ilmenite, leucoxene, rutile, tourmaline, and zircon. Malacon, hyacinth, and the "normal" zircon are present in these sediments. The mineralogical composition of the heavy mineral suite and the degree of rounding of the grains

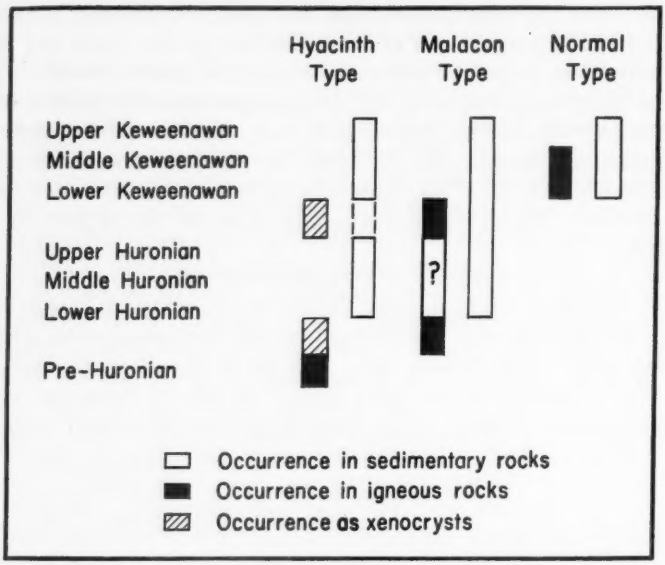

FIGURE 7.—*Distribution of the hyacinth, malacon, and "normal" types of zircon in the rocks of the Lake Superior region*

are very similar to that found in the lower Orienta of the Bayfield group.

SANDSTONES OF FELCH DISTRICT

In the Felch district of Michigan small areas of sandstone unconformably overlie the Huronian formations. This sandstone may be either Keweenawan or Cambrian.

The heavy minerals are dominantly ilmenite, leucoxene, tourmaline, and zircon, with anatase, apatite, epidote, hornblende, and rutile in small quantities (Table 6). In some samples fresh irregular lath-shaped hornblende grains are rather abundant. The zircon appears to be dominantly of the "normal" type, with an occasional deeply colored grain of hyacinth. The heavy minerals indicate nothing concerning the age of these sediments beyond the fact that they are Keweenawan or younger.

SUMMARY OF DISTRIBUTION OF HYACINTH, MALACON, AND "NORMAL" TYPES OF ZIRCON ON THE SOUTH SHORE

Figure 7 shows the stratigraphical distribution of the three main types of zircon in the sedimentary and igneous rocks in the area south of Lake Superior. The occurrence of the more or less rounded hyacinths in the older pre-Huronian granite of the Michigan-Wisconsin region and its distribution throughout the Huronian sediments are comparable with the classical case presented by Mackie (1925, p. 200-213) of the "purple" zircons of the sedimentary rocks of Scotland. This same variety of zircon was previously noted by Tyler (1936, p. 55-84) from the Cambrian and Ordovician sandstones of Wisconsin.

An assemblage of zircons dominated by malacon seems characteristic of late pre-Huronian and Huronian intrusive rocks and is found as detrital grains in the Huronian and Keweenawan sediments.

The "normal" variety of zircon, which first occurs in the Lower Keweenawan sandstone where it probably was derived from early flows, is common in nearly all the Keweenawan igneous and sedimentary rocks of the region.

DATA FROM MINNESOTA

BY F. F. GROUT AND G. A. THIEL

GIANTS RANGE GRANITE

GENERAL NOTES

The Giants range granite lies north of the Mesabi iron-bearing rocks about 100 miles northwest of Lake Superior. It intrudes the Keewatin greenstone and the Knife Lake slates but is unconformably overlain by the Animikie series. Intrusives of these relations were named Algoman by Lawson, and the Giants range granite is an outstanding example of a formation which shows its relations to such sediments.

The general petrography of the Giants range batholith was described by Allison (1925). The mass is characterized by a succession of facies (Pl. 1). Basic rocks occur in small scattered masses as border facies and perhaps as an upper facies. There are both gradual transitions and abrupt contacts with the granites of the main mass. Large areas, especially at the edge and in the east half of the batholith, are monzonite, syenite, and hornblende granite, but a lighter-colored biotite granite is a later facies, and all are cut by aplite and pegmatite. The eastern hornblendic rock is intruded at some places by a porphyritic facies without chilled contacts and with minerals that are so similar that it is probably not much different in age. The main areas of biotite granite lie (1) between Mountain Iron and Chisholm, and (2) southwest of Idington. In

the field the exact limits of the several facies are uncertain at many places because of glacial drift. Some of the boundaries shown in Plate 1 are only rough approximations.

Along the north side of the batholith west of St. Louis County exposures are few, and there seem to be satellitic areas of granite or large pendants of the roof rocks in the granite. Farther east near Birch Lake a granite gneiss that looks distinctly older is surrounded by the more abundant facies of the batholith. This recalls the fact that many batholiths seem to have risen into areas occupied by older batholiths (Moore, 1931). The samples taken for this study may be of several different ages. In spite of this, the area is a unit on the map, and exposed contacts show that some parts of the composite mass are Algoman (post-Knife Lake and pre-Animikie), and no contacts prove that any part is older or younger. This is of course no proof that all of the mass is Algoman, but no attempt was made to treat the mass in any way other than as one composite batholith.

South of the batholith the Keewatin greenstone and Knife Lake slate stand with nearly vertical schistosity in the walls of the granite, but they are exposed at few places, because the Animikie beds, with gentle south dips, cover much of the older formations. Where the Animikie overlaps on the granite, the southern schist wall of the granite is entirely concealed. Seven samples were taken of the basement schist complex, because these rocks may have contributed minerals to the Animikie. All samples of the Giants range and other igneous rocks and basement complex in Minnesota are given numbers prefixed by N- in the tables, and upright numbers on the map. Numbers for sediments are given the prefix P-, and inclined numbers on the map.

The western biotite granite intrudes the eastern hornblendic rock at several places near the center of the range. Samples N-47, 48, 60, 61, and 66 show inclusions of hornblendic granite gneiss in the biotite rock.

The present study of heavy minerals shows some correspondence with these major field distinctions and serves to subdivide the mass according to certain mineral assemblages (Pl. 1).

HEAVY MINERALS

The list of heavy minerals in the Giants range granite includes, besides the abundant biotite, hornblende, epidote, zoisite, augite, chlorite, and muscovite, the following accessory minerals: allanite(?), apatite, carbonates, epidote, fluorite, garnet, hematite and limonite, leucoxene, magnetite and ilmenite, pyrite (and chalcopyrite, pyrrhotite, and galena), rutile, sphene, tourmaline, and zircon. A few grains remained unidentified, chiefly those with alteration to a dusty zoisite or iron oxide. These

would not make a significant error in the mineral proportions. (*See* Table 7.)

Garnet appears in nearly one-third of the samples. Allanite appears in a few, and introduced carbonate and pyrite (and other sulphide) in small amounts in nearly half the samples.

Clearly the prominent and persistent nonmagnetic heavy accessory minerals of the granite are apatite, zircon, and sphene; their proportions are plotted in Figure 8. This figure shows not only the variety of ratios of the three heavy accessory minerals but shows their proportions in the two principal facies by two different symbols. There is added a third symbol for the proportions in the sediments above the granite.

Several minerals are so rare that they were discovered only once in a study of 100 samples: anatase, galena, pyrrhotite, and rutile. Fluorite and tourmaline were each noted in only one or two samples, even after a special attempt was made to collect the smaller pegmatites which might have made up 0.5 per cent of some outcrops and might have contained these pegmatite minerals. Tourmaline needles are abundant at places in the schist walls. Very possibly tourmaline was introduced into the schist from the granite magma, for one large granite sample had abundant recognizable tourmaline. In one sample (N-44) where zircon is recorded, xenotime was suspected because part of it was attracted by a strong magnet; the relief leaves its identity uncertain.

The minerals not found in the granite may be almost as significant as those found. There is an absence of monazite, barite, sillimanite, andalusite, topaz, and brookite which have been reported by other workers in granites from other districts.

In the heavy separates of granite, biotite dominated in about half, and hornblende in the other half; epidote rose to dominance in only three of the 100 samples, and magnetite in three others. Apatite and sphene were the only other normal minor accessory minerals that constituted over 5 per cent of the heavy minerals, and these were not so abundant except in a few granites. Muscovite and chlorite are exceptional because their specific gravities are so near that of bromoform that a variable percentage floats. The results, while not to be considered accurate, affect the percentages in Tables 7, 9, and 11, only in the abundant heavy minerals, and do not modify the ratios of the heavy accessories in any way.

The "Index number" suggested by Brammall referring to Groves (1930) is essentially the number in the second column of Table 7. For many rocks the index number (the percentage of heavy minerals in the washed powder) includes a flood of common hornblende, epidote, or biotite, and the numbers range so widely that they are of little value. Attempts were made to use other indices somewhat as suggested by Wright (1932), but

FIGURE 8.—*Relative amounts of zircon, apatite, sphene, and epidote*

(a) Relative amounts of zircon, apatite, and sphene in two facies of Giants Range granite and in sediments above the granite. Sphene is largely lost, and apatite reduced in sedimentation.

(b) Relative amounts of zircon, apatite, and epidote in two facies of Giants Range granite and in sediments above the granite. Both epidote and apatite are reduced in sedimentation.

TABLE 7.—*Heavy minerals of the Giant's range granite, Minnesota*

Sample No.	% Heavy mineral in washed sample	Mineral percentage of heavy separates: Hornblende and Augite	Biotite and Chlorite	Heavy Muscovite	Epidote and Zoisite	Pyrite and Hematite	Accessories	Percentage of each mineral in heavy accessories: Zircon	Sphene	Apatite	Ilmenite and Leucoxene	Magnetite and Hematite	Garnet	Others
Area B_1														
N-2	1.7	Tr.	67	17	Tr.	.....	15	.....	.....	3	22	73	.....	C–Pr. U–Pr.
N-6	1.3	Pr.	32	8	1	Tr.	58	1	.....	3	68	25	.....	U–2
N-11	11.3	Pr.	69	1	22	.....	7	5	54	32	4	1	.....	F–1 U–1
N-19	12.7	39	53	.....	Pr.	.....	7	6	32	27	10	26	.....	
N-38	1.7	Pr.	76	10	Pr.	.....	14	14	.....	25	54	5	.....	U–2
N-52	5.0	11	68	Tr.	10	Tr.	11	4	7	12	17	60	.....	
N-59	6.5	1	71	.....	20	Pr.	8	5	5	36	43	9	.....	U–1
N-61	5.1	49	36	Pr.	8	Tr.	6	2	9	31	27	29	.....	U–2
N-66	2.6	24	63	3	1	Tr.	8	5	6	51	27	10	.....	
Area Bp														
N-10	2.1	Pr.	27	3	11	Tr.	59	3	Pr.	9	16	71	Tr.	U–Pr.
N-17	2.2	3	58	1	6	.....	32	1	6	6	13	73	.....	C–Tr. U–1
N-24	1.2	5	61	13	1	.....	20	4	1	19	42	33	.....	C–1 U–1
Area B_2														
N-27	2.3	15	66	16	Tr.	.....	3	19	16	32	7	19	.....	U–7
N-28	2.7	6	78	9	Pr.	Tr.	6	9	3	33	21	21	10	U–3
N-29	0.7	3	59	22	2	.....	15	5	.....	61	18	5	7	All–Pr. C–Pr. U–2
N-30	1.1	1	75	13	4	Tr.	7	9	2	76	6	2	5	U–2
N-39	1.9	Tr.	81	2	2	.....	15	10	Pr.	30	31	24	Pr.	F–Pr. R–Pr. U–1
N-40	1.1	1	81	11	Pr.	Tr.	6	2	2	27	36	23	5	C–5 T–2
N-41	0.6	1	73	14	1	.....	12	9	.....	28	43	21	.....	
N-42	0.8	Pr.	75	12	Pr.	.....	11	12	.....	22	54	12	.....	
N-43	2.9	Pr.	46	8	9	.....	35	8	Tr.	8	16	68	Tr.	U–Tr.
N-44	0.7	Pr.	56	27	1	.....	16	12	1	6	32	39	10	
N-45	0.8	1	43	25	4	.....	28	2	.....	7	37	48	1	U–4
N-46	0.3	Tr.	37	27	4	12	21	8	.....	3	41	34	10	C–2 U–3
N-47	1.4	Tr.	60	31	Pr.	.....	8	10	.....	12	22	7	48	U–1
N-48	14.0	25	67	Pr.	6	.....	2	4	26	65	.....	.....	4	
N-49	2.7	Pr.	88	9	Tr.	Tr.	3	8	.....	69	15	4	4	
N-50	3.9	Tr.	59	Pr.	17	Tr.	23	5	Tr.	15	9	69	Tr.	U–Tr.
N-51	5.3	6	71	Pr.	12	Tr.	10	4	20	22	3	47	3	U–2
N-53	7.2	Tr.	70	2	11	Tr.	16	1	4	17	6	70	1	T–2
Area Bsp														
N-31	2.3	Pr.	88	5	Pr.	.....	6	15	.....	31	27	22	2	U–3
N-34	1.4	8	42	4	8	Tr.	39	3	1	11	19	64	Pr.	All–Tr. U–Pr.
N-35	3.4	Pr.	61	Pr.	1	Tr.	36	3	2	15	13	64	.....	All–Tr. U–Pr.
N-36	2.4	3	75	1	1	Tr.	20	9	2	25	19	45	.....	U–Pr.
N-37	1.6	Tr.	86	6	Tr.	.....	8	9	3	36	48	1	.....	All–1 U–1
Area H_1														
N-60	16.0	42	41	.....	13	Tr.	4	.....	21	23	19	37	.....	
N-68	16.2	59	25	Pr.	11	.....	5	4	29	41	8	16	.....	U–2
N-70	25.1	67	21	Pr.	7	.....	5	8	29	54	2	.....	2	C–2 U–4
N-71	12.6	48	39	Tr.	7	.....	6	4	13	14	9	61	.....	
N-77	23.4	78	5	Tr.	7	Tr.	9	.....	14	29	8	50	.....	
N-83	14.3	56	30	.....	3	.....	11	4	16	23	5	51	.....	
N-95	28.0	62	24	.....	2	.....	13	Pr.	16	25	2	57	.....	
N-102	30.7	68	20	Tr.	2	.....	10	.....	14	24	.....	62	.....	
N-120	49.6	85	4	.....	5	1	5	1	1	3	4	67	.....	Altrd–23 U–Pr.
N-121	46.6	42	32	.....	19	.....	7	1	1	14	6	66	.....	U–11
N-122	74.9	97	1	Tr.	Pr.	.....	1	.....	.....	7	.....	79	.....	U–14
N-123	4.6	73	4	.....	4	Tr.	19	Pr.	2	13	8	75	.....	U–2
N-124	12.7	28	42	Tr.	6	Pr.	23	Tr.	Tr.	12	.....	85	.....	U–3

U–Unknown R–Rutile T–Tourmaline Pr.–Present Tr.–Trace
C–Carbonate F–Fluorite All–Allanite (0.5 to 0.9%) (0 to 0.4%)

TABLE 7.—*Heavy minerals of the Giant's range granite, Minnesota*—Continued

Sample No.	% Heavy mineral in washed sample	Mineral percentage of heavy separates						Percentage of each mineral in heavy accessories						
		Hornblende and Augite	Biotite and Chlorite	Heavy Muscovite	Epidote and Zoisite	Pyrite and Hematite	Accessories	Zircon	Sphene	Apatite	Ilmenite and Leucoxene	Magnetite and Hematite	Garnet	Others
Area Hp														
N–80	12.7	70	19	Tr.	3	.....	7	4	8	22	27	36	.....	C–1 U–1
N–81	18.1	50	31	Pr.	8	.....	10	1	25	13	5	55	.....	U–1
N–85	14.0	84	1	.....	6	Tr.	8	4	37	22	5	32	.....	
N–86	4.6	52	9	Tr.	32	.....	8	3	18	26	30	23	.....	U–1
N–87	10.4	35	46	.....	Pr.	.....	19	1	1	17	15	59	6	U–Pr.
N–88	16.5	70	13	.....	1	.....	16	Pr.	12	19	.....	68	.....	
N–89	21.2	36	32	.....	15	.....	17	1	17	19	2	61	.....	
N–98	8.1	51	18	.....	4	.....	28	1	18	11	3	66	.....	U–Tr.
N–99	2.6	5	62	.....	2	Tr.	31	2	4	17	17	60	Tr.	U–Pr.
N–100	1.8	21	16	.....	17	.....	47	2	16	15	10	56	.....	U–Tr.
N–101	5.8	6	46	.....	40	.....	9	2	12	29	21	34	.....	U–1
N–103	9.8	43	33	.....	4	.....	20	1	9	19	21	48	.....	U–1
N–104	8.0	2	88	.....	2	.....	9	2	1	42	41	1	.....	C–8 Altrd–4
N–105	17.1	66	15	Tr.	7	.....	13	Pr.	8	24	6	60	.....	C–2
Area H_2														
N–90	4.2	68	15	.....	3	Tr.	14	1	30	30	21	15	.....	U–1
N–91	13.8	81	2	.....	5	.....	12	2	34	19	8	37	.....	
N–92	9.8	76	3	.....	8	.....	13	Pr.	25	22	46	7	.....	
N–93	12.7	84	4	.....	4	Tr.	8	3	29	32	20	17	.....	
N–94	1.7	2	Pr.	.....	6	.....	91	Pr.	Tr.	6	1	Tr.	Tr.	A–1 Altrd–91
Area H_3														
N–75	30.8	70	1	.....	21	.....	8	1	9	16	17	57	.....	
N–78	27.8	61	4	Tr.	26	.....	9	1	4	12	27	53	1	U–1
Area H_4														
N–67	27.3	65	22	.....	8	.....	5	2	28	60	.....	10	.....	
N–69	21.1	73	16	.....	6	.....	5	2	18	34	16	30	.....	
N–73	17.0	68	19	.....	10	.....	4	.....	34	46	14	3	.....	U–3
N–76	18.9	68	14	Tr.	6	.....	12	3	12	14	25	44	.....	U–Pr.
Area H_5														
N–62	28.2	70	17	Tr.	3	.....	10	1	32	47	4	14	Tr.	U–1
N–63	28.9	70	20	.....	3	Tr.	7	.....	26	46	12	16	.....	
N–64	10.5	55	18	Pr.	15	.....	11	2	21	52	8	15	Tr.	U–Pr.
Area H_6														
N–12	30.9	70	23	Tr.	4	Tr.	3	3	38	53	3	3	.....	
N–13	21.0	78	14	.....	3	.....	5	7	33	28	26	4	.....	C–2
N–14	24.7	84	13	.....	Pr.	.....	2	5	36	36	14	9	.....	
N–20	8.8	Pr.	87	4	Pr.	Tr.	8	3	.....	39	44	9	.....	C–3 U–3
N–22	43.5	85	12	.....	Pr.	.....	3	7	21	59	7	3	.....	U–3
N–23	22.1	81	14	.....	2	.....	4	3	33	44	17	3	.....	
N–25	27.4	76	17	.....	2	.....	6	2	38	15	4	36	2	U–4
N–26	80.1	98	Tr.	.....	Tr.	Tr.	2	6	81	13	.....	.....	.....	
N–33	38.8	81	2	Tr.	16	Tr.	1	23	62	8	.....	.....	.....	U–8
Area H_7														
N–7	2.9	Tr.	43	5	Pr.	.....	51	5	.....	18	40	37	.....	U–1
N–8	36.6	64	10	Tr.	21	Tr.	5	2	51	11	8	22	.....	U–6
N–9	10.7	.....	67	Tr.	19	Tr.	14	6	53	26	6	.....	.....	U–9
Area H_8														
N–1	9.3	2	79	Tr.	5	.....	14	1	14	13	4	67	.....	U–Pr.
N–3	8.4	3	84	Tr.	3	.....	10	4	17	22	13	42	.....	U–1
N–4	5.0	3	73	1	11	.....	12	2	16	14	7	60	.....	U–Pr.
N–5	8.2	33	49	.....	3	.....	14	1	5	11	22	56	.....	U–4

U–Unknown
C–Carbonate
A–Anatase
Alt–Altered aggregates
Pr.–Present (0.5 to 0.9%)
Tr.–Trace (0 to 0.4%)

TABLE 7.—*Heavy minerals of the Giant's range granite, Minnesota*—Continued

Sample No.	% Heavy mineral in washed sample	Mineral percentage of heavy separates						Percentage of each mineral in heavy accessories						
		Hornblende and Augite	Biotite and Chlorite	Heavy Muscovite	Epidote and Zoisite	Pyrite and Hematite	Accessories	Zircon	Sphene	Apatite	Ilmenite and Leucoxene	Magnetite and Hematite	Garnet	Others
Area H_9														
N-15	16.6	19	66	Tr.	5	.....	10	1	24	17	3	49	.....	U-7
N-16	11.4	33	51	Tr.	3	.....	13	3	4	10	7	75	.....	U-2
N-18	72.9	97	.....	Tr.	2	.....	Pr.	.....	78	.....	.....	22	.....	
Old (?) Gneiss														
N-79	10.5	Tr.	91	2	2	1	3	6	42	6	45	.....	.....	
N-82	0.8	Pr.	61	.....	5	.....	33	6	4	41	40	9	.....	U-Pr.
N-96	13.1	17	72	Pr.	6	Pr.	4	5	16	68	3	5	3	
N-97	23.7	44	46	Pr.	6	Tr.	4	3	28	46	10	11	.....	U-3
N-106	11.4	80	15	.....	3	.....	3	.....	8	20	52	12	.....	U-8
Apophyses														
N-54	1.1	Tr.	54	25	6	2	13	4	Pr.	32	49	7	.....	C-7 U-Pr.
N-55	0.7	Tr.	3	40	1	3	52	2	.....	16	78	3	.....	C-Pr. U-Tr.
N-56	1.4	Tr.	11	47	3	17	21	4	.....	10	85	.....	.....	U-1
N-74	29.6	89	4	.....	7	.....	1	7	29	57	7	.....	.....	
Basement Complex														
N-21	65.2	89	5	.....	5	Tr.	Tr.	.....	.....	67	.....	.....	.....	C-33
N-32	74.7	89	5	.....	2	.....	4	10	44	39	7	.....	.....	
N-57	34.2	1	97	Tr.	Tr.	Tr.	Pr.	.....	.....	.....	100	.....	.....	
N-58	22.9	Too	much	alter	ed to	count								
N-65	72.3	92	2	Tr.	5	Tr.	1	.....	.....	9	73	9	.....	U-9
N-72	5.0	3	92	.....	1	1	3	3	.....	16	77	.....	3	T-Tr.
N-84	0.6	6	63	.....	3	3	25	5	1	16	65	11	.....	U-1

C–Carbonate U–Unknown Tr.–Trace (0 to 0.49%)
T–Tourmaline Pr.–Present (0.5 to 0.99%)

these numbers also range widely, and neither the whole mass or any of its major facies has a reasonably constant index. Little relation could be found between the index number and the appearance of coarse feldspar phenocrysts as has been suggested elsewhere (Brammall and Harwood, 1923; Wright, 1932, p. 256), but the finer-grained biotite granite has a notably lower index than the coarse hornblende rock, making it comparable to some observed in other districts (Brammall and Harwood, 1923; Boos, 1934, p. 326).

DESCRIPTION OF ABUNDANT HEAVY MINERALS

BIOTITE: Biotite is brown to greenish-brown, and in some slides a few grains are stained or altered to a darker, redder shade resembling allanite. It is the chief

varietal mineral in much of the central and west parts of the range but is less abundant at the east, where hornblende dominates. Where biotite is the varietal mineral, it is rarely over 5 per cent of the rock. Where the two are nearly equal they average 12 per cent of the rock, and where hornblende largely dominates it forms an average of about 25 per cent of the rock; thus the biotite granites are much lighter colored than the hornblende granites. Much of the biotite is partly altered to chlorite, and the extent of alteration ranges so widely that it seemed best to list them together in Table 1.

HORNBLENDE: Hornblende as listed in Table 1 includes green augite, found in two samples (N-62 and N-63) near the center of the range. Both minerals are green and they are distinguished only by their different pleochorism and extinction angles. Augite occurs also in a "gabbro facies" (N-121 and N-123) related to the main mass near the east end. The darker rocks also contain hypersthene.

Green hornblende is the varietal mineral of the east half of the range and of certain local border facies of the west half. A few samples include some slightly brownish hornblende. Sample N-20 is from a hornblende area, but the hornblende has largely disappeared, leaving chlorite and epidote.

Where hornblende dominates notably over other heavy minerals certain other minerals are abundant, notably sphene. If hornblende is less than 10 per cent of the heavy minerals in the washed sample, sphene is in the average .7 per cent; if hornblende is over 50 per cent of the heavy minerals, the sphene average is 2.2 per cent. *See* also Figure 8 which shows that most of the rocks near the sphene corner are hornblendic.

MUSCOVITE: Muscovite was rarely noted in the field but appears in many of the nonmagnetic fractions of biotite granite. It does not commonly appear in hornblende granites. It happens that a few samples taken near the borders of the biotite granite (for examples, N-60, N-61, N-64, and N-66) were from outcrops where fragments of hornblende granite lie in the biotite granite. Such samples show both muscovite and hornblende in the table, but they are composite samples from a mixed outcrop.

EPIDOTE: Epidote is especially abundant in the hornblendic eastern part of the batholith but occurs widely throughout. Probably most of it is secondary, although allanite occurs at some places, and Allison (1925, p. 502) found primary epidote accompanying it.

DESCRIPTION OF ACCESSORY HEAVY MINERALS

ALLANITE: Allanite occurs in some hornblendic facies. An area where the granite contains some biotite resembling allanite lies in the north parts of T. 58 N., Rs. 19 and 20 W., between Buhl and Chisholm.

ANATASE: A single fragment of anatase was found in one sample. It is a yellowish-brown square plate with edges bevelled by pyramid faces.

APATITE: Apatite occurs in all but four of the granite samples. It forms hexagonal prisms ranging in size from .05 to .2 mm. The ratio of apatite grains to others is much greater in the finer sizes than in coarse sizes. Many grains show a faint blue color, and many are stained by limonite or have dusty gray central zones.

CARBONATE: Ferruginous carbonates of secondary origin are widely scattered in small amounts.

FLUORITE: Fluorite is noted in only two samples. It is purplish-blue and in coarse grains.

GARNET: Garnet is in small crystals and fragments, which are pink or rarely yellow. The garnet cannot be related to inclusions of sediments or to contacts and is not necessarily a product of contamination. Some does occur near the schists, but some is far from any known material of that sort. It may be primary and magmatic. Nearly all of it lies west of the center in the areas of biotite granite, but a few grains can be found in the hornblende granites (N-97) far to the east.

MAGNETITE, ILMENITE, AND LEUCOXENE: These minerals occur widely in all facies of the mass, but especially in the hornblendic and porphyritic granites.

RUTILE: Rutile was seen as an alteration product in some chlorite in a thin section, but little was identified with certainty in the bromoform separates.

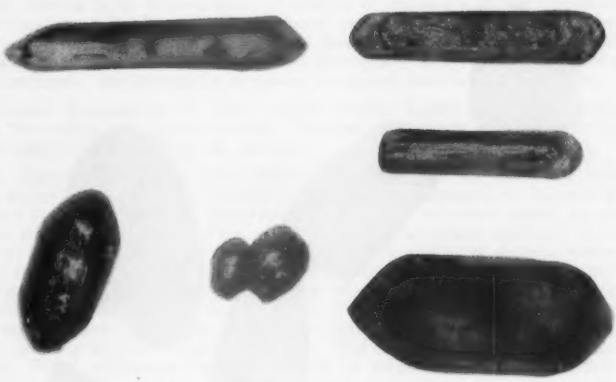

FIGURE 1. FORMS OF HYACINTH TYPE

FIGURE 2. FORMS OF "NORMAL" KEWEENAWAN TYPE

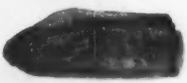

FIGURE 3. HYACINTH WITH LATER GROWTH

ZIRCON CRYSTALS (X 125)

FIGURE 1. TOURMALINE WITH SECONDARY GROWTH
From Pokegama quartzite (X 85).

FIGURE 2. SAGANAGA GRANITE, ABOUT NATURAL SIZE
Quartz (dark gray) is in larger grains than in other Minnesota granites.

TOURMALINE, AND SAGANAGA GRANITE

SPHENE: Sphene is in large angular fragments of crystals and less commonly in small euhedral crystals. It ranges from almost colorless to brown and rarely purple, and the dark grains are notably pleochroic. Most of the sphene in biotite rocks is clear, and that in the hornblende rocks (*see* description of hornblende) is almost as dusty as leucoxene. Several grains of sphene contained minute dark inclusions.

TOURMALINE: Tourmaline in large purplish-brown highly pleochroic fragments occurs in two samples of biotite granite. Smaller, paler-green crystals occur in the basement complex intruded by the granite.

ZIRCON: Zircon grains range from 0.04 to somewhat over 0.2 mm., and most of them are closer to 0.04 mm. If the heavy minerals were screened to separate grains coarser and finer than 0.1 mm., the relative percentages of zircon would be greater in the fine than in the coarse fraction. The dimensions of grains measured in biotite granites are slightly larger than those in the hornblende rocks. It shows a wide range of crystal forms and habits, with zoning and possibly some etching of the surfaces (Pl. 2). Some are long and slender, whereas others are short. Most of the grains show combinations of several forms, giving the small grains the appearance of rounded ends. Many grains are pale brown, pink, purple, or almost colorless, and a few are so dusty that the color is obscured. The more strongly colored grains are pleochroic. These differences show no relation to areas of distinguishable facies of granite. Several kinds may appear in one sample, and several others in an adjacent sample of the same outcrop. There is more variety in the zircons of an outcrop of one facies than difference in different parts of the batholith (Pl. 1, fig. 1). Nearly all samples, however, show the hyacinth type.

One grain of zircon from a granite (N-44) has a corroded-looking brown core with an outgrowth of much lighter zircon in optical continuity (Pl. 2, fig. 3). This closely resembles some sedimentary zircons, supposed to have growths formed after the deposition of the sediments (Butterfield, 1936). The grain here noted could hardly have had such an origin, however, as it was concentrated from a fresh granite with no sign of contamination.

RELATION OF HEAVY ACCESSORY MINERALS TO MAP AREAS

The several subdivisions of the granite mapped in Plate 1 are briefly characterized in the legend, but further details are available in Table 7. Several of the divisions are based on field or hand specimen distinctions, but these are checked, and new divisions added by the study of heavy accessory minerals. Evidently it is possible to subdivide a large area of uniform-looking intrusive by means of a study of heavy accessory minerals.

(B_1) The main western area of biotite granite has less than 5 per cent of biotite, with small percentages of apatite, sphene, and zircon in the common range of proportions. Samples N-60, N-61, and N-66 are hornblendic because of large inclusions of rock like that in the H_1 area.

(B_p) About like B_1 but with feldspar phenocrysts, less biotite, and more magnetite.

(B_2) An area in T. 59 N., R. 18 W., and northwest is sharply distinguished by an assemblage of accessory minerals. Garnet and magnetite are abundant. The sum of apatite, zircon, and sphene is lower than average, but the ratio of zircon to the sum of apatite and sphene is larger than elsewhere.

(B_{2p}) The border of the granite west of B_2 has another distinguishing assemblage. Most of the rocks have phenocrysts of feldspar. A characteristic minor accessory is

allanite (or a stained biotite resembling allanite), which occurs in only a few other places in the batholith. Magnetite is over 5 per cent of the heavy minerals. The total heavy mineral per cent (index figure) is lower than for most of the biotite granite, but the accessory minerals are a little higher than in the other biotite granite areas.

(G) Gabbros seem to be later intrusives, possibly of Keweenawan age, except for an exposure near the east end which grades into the granites.

(H_1) Hornblende granite, partly gneissic, forms the main batholith from the center northeast. There is an average of 13 per cent hornblende in the rock and 60 per cent in the heavy fraction, and even more in some border zones in addition to those mapped by other numbers. The total percentage of heavy minerals (index number) ranges from 12 to 75, and if biotite is present at all it is subordinate to hornblende. Only scattered samples have any allanite, garnet, or muscovite. Many have fairly high epidote, and several have magnetite over 5 per cent of the heavy minerals. Sample N-60 is mixed biotite and hornblende rock, as sampled in the field.

(H_p) In the same general area as H_1, feldspar phenocrysts may make the rock porphyritic without other essential change in its nature. The phenocrysts seem to make this rock different from that in the area H_1 chiefly by leaving less space for the dark minerals; the index numbers are 2 to 22. Several of the porphyritic rocks prove to have more biotite than hornblende, though all have more hornblende than is common in the B_1 area.

(H_2) In this area the five samples taken show some peculiarities in accessory minerals, but they are not uniform through the whole series. Two of the five samples show high epidote, and one high magnetite. Three show a high sum of apatite, zircon, and sphene. Altogether it seems an area of sharp local differences, possibly related to some rather abundant inclusions of altered, hornblendic greenstone.

(H_3) West of the area of older-looking gneiss, the main features of the hornblende granite are also slightly modified. A few miles northwest of Mesaba the rock is porphyritic and has chlorite rather than hornblende or biotite. There is also a sample low in hornblende but epidotic.

(H_4) Along the south side of the hornblendic granite in Rs. 16 and 17 W. there is a belt of dark hornblende rocks, syenites in part. Several of these have only small percentages of accessory minerals other than hornblende and epidote, but one has considerable magnetite.

(H_5) Near Idington several samples are dark with hornblende but have phenocrysts of alkalic feldspar. Garnet, allanite (?), and more than ordinary proportions of sphene occur here. If the high percentage of accessory minerals other than magnetite is characteristic of this area, it may extend through T. 60 N., R. 17 W., farther southeast than is shown. Its limits on the west also have not been closely determined, because glacial drift conceals much of the granite.

(H_6) South of the biotite granite area, this distinct area of hornblende rocks lies in Rs. 20 and 21 W. It has all three of the main characters of H_1—dark in hand specimen, high ratio of hornblende to biotite, and index number (percentage of heavy minerals) over 10. Several samples show also more sphene than any of the biotite granite samples near by. Zircon and garnet may in one or two samples be more abundant than in any of the near-by samples outside the area.

(H_7) In this area along the south side of the biotite granite accessory minerals and hornblende are more abundant than in the B_1 area, and in one sample hornblende largely dominates.

(H_8) A border area in R. 25 W. has more magnetite in the heavy assemblage than adjoining areas. All these rocks have more hornblende than the B_1 area, but biotite is still dominant.

(H_9) In T. 59 N., R. 22 W., west of a schist area, some hornblende granite crops out near the supposed north side of the mass, but outcrops are few, and relations obscure; part of the rock has both biotite and hornblende.

Samples of the basement complex near the Giants range granite show some "hyacinth", but no other distinguishable variety is abundant.

POKEGAMA QUARTZITE

GENERAL NOTES

The main portion of the Animikie series in Minnesota is the Biwabik iron-bearing formation of the Mesabi range and the overlying Virginia slate. Below these, however, there was deposited a sand of more normal sedimentary character than the cherty iron-bearing rocks. This is the Pokegama quartzite, and it has at its base a conglomerate which shows pebbles from the underlying formations. The unconformity near the east end of the range was questioned by Richarz (1930), and more recently by Leith, Lund, and Leith (1935) who correlate the granite with the Keweenawan. The exposures seen by Grout and Broderick (1919), after a forest fire had cleaned the outcrops, and more recent field studies by members of the Minnesota Geological Survey have convinced the workers in Minnesota that the sediments were deposited on the granite. It seems more than probable, therefore, that this sediment derived a good deal of its material from the Giants range batholith, although some was no doubt from the greenstone and slate, and some from more distant formations.

The Pokegama quartzite rests with a marked angular unconformity on the truncated folds of the Knife Lake series of slates and graywackes, on the Algoman granites, and on the Archean greenstones. The quartzite outcrops are located in a belt between the north margin of the iron formation and the ridge of granites and older rocks of the Giants range. There are differences in the angle of dip, and the width of outcrop of the quartzite in some places may be as great as 3000 feet; in other places the formation does not crop out because the iron formation overlaps onto the older rocks to the north. The Pokegama formation ranges from a few feet to over 200 feet in thickness. It includes vitreous quartzite of various colors and textures, micaceous quartz slates, and conglomerates.

The common basal beds of the Pokegama quartzite are typical basal conglomerate (Fig. 9) that forms a very irregular layer from a few inches to 8 feet thick. In general the conglomerate contains pebbles and boulders representing the various facies of the older rocks of the region. At nearly every outcrop of conglomerate, pebbles of the immediately subjacent rocks predominate.

The basal conglomerate layers grade upward into thin-bedded slaty quartzites or quartzitic slates. These slates commonly contain a considerable amount of mica along bedding planes. Muscovite is abundant in the lower slaty layers in the north wall of the Biwabik open pit, in

the slaty layers in the quarry at the north edge of the city of Eveleth, and in the lower slaty facies on the floor of the quarry north of the Hull-Rust pit at Hibbing. There are layers of similar slaty material at higher horizons where they overlie massive quartzite.

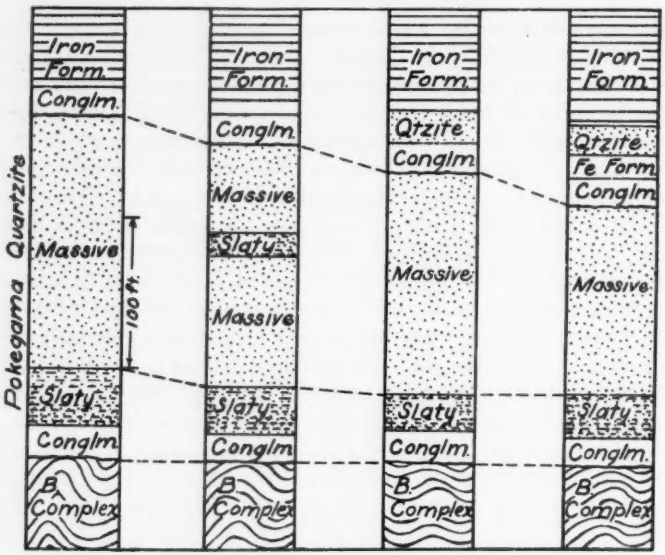

FIGURE 9.—*Geologic columns of exposed Pokegama quartzite*

Near the top of the Pokegama formation thin layers of ferruginous chert are interbedded with the quartzite. At several places iron oxides replace the upper part of the quartzite, at others a thin but persistent layer of conglomerate separates the quartzite from the overlying iron formation, and at a few locations some sand was deposited over the conglomerate before the ferruginous cherts of the Biwabik formation were laid down. A drill hole in the SW¼ SE¼ sec. 39, T. 59 N., R. 17 W., penetrated iron formation, quartzite, conglomerate, and quartzite in the order given (Leith, 1903, p. 154).

Thirty-seven samples were collected from outcrops of the Pokegama formation, and 10 samples were taken from the formation in diamond drill cores that were obtained through exploratory drilling for iron ore. The quartzite cores were taken from the upper part of the formation, immediately below the iron formation. The geographic distribution of

the samples is shown in Plate 1; their stratigraphic position is given in Table 2.

The samples, all marked with "P" before the number, represent four facies of the Pokegama formation.

(1) Samples 1-13, 17, 19, 21-26, 30, 32, and 33 were taken from massive, medium- to coarse-grained pink, red, or purple quartzite.
(2) Samples 14, 16, 18, 29, 31, 34, 36-38, 44, 45, and 47 are medium- to coarse-grained and gray to greenish gray.
(3) Samples 15 and 39-43 are thin-bedded, slaty and shaly facies some of which are gray and others yellowish brown.
(4) Samples 20 and 46 are conglomeratic facies near the base of the formation.

ACCESSORY MINERALS

The heavy minerals in the Pokegama quartzite are anatase, apatite, epidote, hornblende, leucoxene, magnetite, muscovite, pyrite, tourmaline, sphene, tremolite, and zircon. Other minerals that appeared in only a few samples are rutile, galena, diopside, monazite, fluorite, collophanite, and greenalite. Tourmaline dominated in 13 samples, zircon in 10, apatite in 5, and hornblende in 3. One sample of accessory minerals contained more than 50 per cent anatase, and one contained 46 per cent magnetite. A few grains remained unidentified, and the percentage of the total is shown in Table 8.

The distribution of minerals in the heavy accessory separate, after the magnetic fractions were treated with HCl, is shown in Table 8. Hematite and chorite grains were ignored in making the mineral counts. Differences in the proportions of accessory minerals common to both granite and quartzite are shown graphically in Figures 8A and 8B.

A test was made of the light minerals of the Pokegama by finer grinding and repeated treatment in bromoform, but the crop of heavy minerals included in the light minerals was much like that first obtained from the sand.

ANATASE: Most of the anatase occurs as euhedral pyramids with striated faces. They range in size from ¼ to 1/16 millimeter. A few grains are brown, but the floods are pale blue. The euhedral grains may be authigenic, derived from recrystallization of other titaniferous minerals.

APATITE: Apatite is mainly in the form of rounded, prismatic grains. Most of the grains are small, transparent, and colorless. A few are up to ¼ mm. thick.

EPIDOTE: Epidote occurs mainly as pale greenish-yellow, pleochroic, irregular and somewhat angular grains. There are some transparent grains, but much of the mineral is in dusty, light-colored, granular aggregates.

GARNET: Only a few grains of garnet occur in the quartzite. Crystals are dodecahedral and pink to brownish-red. Some grains are clearly detrital.

HORNBLENDE: Hornblende grains are conspicuously elongated and angular, with frayed and splintery ends. They are larger than the other heavy accessory minerals. Most grains are dark green and moderately pleochoric. In a few samples a blue-green, strongly pleochroic variety shows optical properties suggesting a sodic variety.

TABLE 8.—*Heavy minerals of the Pokegama quartzite*

Sample number	Percentage by weight of heavy minerals before and after HCl treatment of the magnetic fractions: % by wt. of heavy minerals First separation	% by wt. of heavy minerals After HCl	Relative Abundance before Acid Treatment: Chlorite	Hematite	Pyrite	All other accessories	Distributions of minerals in the heavy accessories based on number of grains (Chlorite, hematite, and pyrite excluded): Anatase	Apatite	Epidote	Garnet	Hornblende	Leucoxene	Opaques	Tourmaline	Sphene	Zircon	Miscellaneous
Top of Formation																	
P7	.05	.03	P	F	P	A	25	1	7	....	6	7	....	35	1	13	U–5
P8	.06	.01	P	F	P	A	26	4	6	1	9	2	3	26	Pr.	22	
P11	1.21	.01	P	F	P	A	Pr.	30	2	....	35	11	4	....	....	10	B–Pr. U–6
P12	.44	.01	P	F	C	C	2	15	3	....	29	3	3	2	2	27	R–8 D–6
P13	34.13	.02	P	F	P	A	1	3	2	31	20	3	12	....	3	11	R–2 U–11
P31	N.D.	N.D.	F	P	P	A	2	16	4	....	14	2	6	8	2	36	U–10
P32	1.36	.04	P	F	P	A	1	1	7	....	15	10	3	34	....	27	
P33	100.00	.01	F	F	P	A	....	....	11	3	6	16	....	22	1	36	U–5
P34	7.70	.07	F	P	A	P	2	7	6	2	16	3	8	27	....	20	U–8
P35	.91	.12	F	A	A	P	....	28	3	2	32	....	9	5	....	5	U–14
P36	1.59	.02	F	P	P	A	4	3	16	4	22	9	1	12	....	28	B–Pr.
P37	3.67	.16	P	F	P	A	2	Pr.	15	....	7	3	2	35	Pr.	32	U–2
P38	.58	.05	F	P	P	A	....	3	5	....	11	9	5	28	....	39	U–Pr.
P47	.31	.06	F	P	P	A	....	....	8	1	Pr.	4	....	39	....	45	M–2 U–1
Main Body of Formation																	
P1	.55	.01	P	F	P	A	2	2	13	2	4	9	48	2	Pr.	13	U–5
P2	1.77	.29	P	F	A	C	....	22	18	4	27	2	2	Pr.	Pr.	14	U–10
P3	.06	.01	P	F	P	A	26	5	10	2	10	1	....	19	1	17	R–3 U–5
P4	.25	.02	P	F	P	A	8	32	11	1	19	2	4	16	....	7	
P5	.27	.04	P	F	P	A	1	59	7	2	11	....	1	3	1	6	U–9
P6	.17	.02	F	A	P	P	4	41	22	....	11	2	2	12	1	4	G–1
P9	.34	.01	P	F	P	A	2	2	26	....	5	6	....	46	....	9	U–2
P10	.16	.02	C	F	P	P	20	5	23	....	17	3	....	23	....	9	
P14	.52	.09	A	A	A	P	....	8	1	Pr.	11	4	7	28	....	34	U–7
P15	.19	.08	F	P	....	A	2	1	10	....	1	1	2	45	....	36	U–2
P16	.64	.05	P	F	P	A	14	1	3	2	9	7	2	37	....	25	
P17	.77	.02	P	F	P	A	6	....	29	....	5	1	2	42	Pr.	10	M–1 U–2
P21	.33	.01	P	F	P	A	29	36	11	....	4	8	....	1	....	5	B–5 U–2
P22	.62	.04	P	F	P	A	7	48	1	....	28	....	5	....	3	7	U–2
P23	.76	.04	P	F	P	A	17	24	19	....	7	....	....	2	2	23	R–Pr. U–4
P24	.65	.02	P	F	P	A	2	12	13	1	35	....	3	3	2	29	
P28	1.13	.03	C	F	P	C	18	4	5	....	18	7	1	16	....	31	
P29	1.01	.01	F	P	P	A	....	2	15	....	8	7	....	....	3	21	D–35 U–7 B–1
P30	.15	.01	P	F	P	A	53	6	3	1	9	7	5	5	....	10	U–1
P44	54.28	41.06	P	P	....	F	....	Tr.	....	....	....	....	....	....	....	Tr.	A–99
P45	.24	.05	F	P	P	A	....	30	21	....	4	Pr.	....	....	....	24	D–17 U–3
Near Bottom of Formation																	
P18	.25	.02	P	F	P	A	27	3	7	....	12	3	4	33	2	9	
P19	.34	.01	C	F	P	C	36	....	4	....	4	....	....	44	....	9	U–3
P20	54.85	.12	F	P	P	A	Pr.	6	1	Tr.	1	4	13	1	....	3	C–70
P25	.07	.03	P	F	P	A	11	Pr.	15	....	5	5	1	23	....	33	B–Pr. U–5
P26	.13	.02	P	F	P	A	11	1	3	....	9	14	2	30	1	29	
P27	N.D.	N.D.	P	F	P	A	3	....	6	1	5	7	....	27	2	44	B–2 U–3
P39	.07	.02	F	P	P	A	Pr.	2	6	....	2	4	2	28	1	50	U–3
P40	.14	.06	P	P	P	F	....	....	7	....	3	14	2	27	2	43	D–1 B–Pr.
P41	3.46	.07	P	A	P	A	....	4	8	....	36	....	34	3	....	4	M–Pr. U–9
P42	.80	.12	P	F	P	A	....	5	25	2	35	5	3	13	1	10	
P43	.74	.14	P	A	....	A	....	....	....	....	2	....	....	27	2	33	D–31 U–3
P46	26.64	1.76	F	P	....	C	....	4	6	Pr.	36	2	4	....	....	....	C–47

F–flood (more than 50%)
A–abundant (30%–50%)
C–common (15%–30%)
P–present (0%–15%)

D–Diopside
U–Unknown
R–Rutile

G–Galena
B–Biotite
A–Amphibole

M–Monazite
C–Collophanit

LEUCOXENE: Leucoxene occurs in small amounts as rounded rough and irregular white or yellowish-white aggregates in nearly all the samples of the quartzite.

MAGNETITE: Most of the magnetite grains are small and somewhat rounded. A few show crystal outlines. Some are partly altered to martite, and others are coated with red hematite.

PYRITE: Pyrite forms crystals and aggregates. In some of the dark-gray facies of the quartzite, pyrite cubes measure more than half an inch on an edge. There are many pseudomorphs of limonite after pyrite in the weathered quartzite.

TOURMALINE: The tourmaline is mainly in oval and rounded prismatic grains that are brown and brownish-black and strongly pleochroic. A few grains are blue and bluish-gray. Many of the smaller grains are subrounded, but few show remnants of crystal outlines. Secondary growths of lighter color are conspicuous on many of the grains.

SPHENE: The sphene is in yellowish-brown to brown irregular and angular grains. Some are well rounded, others are crudely diamond-shaped.

ZIRCON: Zircon is one of the most persistent accessory minerals in the quartzite. Most of the grains are less than 1/16 millimeter in diameter. They show a variety of forms ranging from well-rounded and oval grains to long, needlelike crystals with distinct terminal faces. Many were broken during the crushing. Most of the grains are colorless; others are pale brown, and still others, pale rose-pink to purple—the hyacinth type. Some of the larger grains are beautifully zoned.

RUTILE: Rutile is not an abundant accessory mineral in the quartzite. A few large, irregular, reddish-brown grains were observed in some of the samples. Smaller grains occur as aggregates of minute acicular crystals radiating from a brownish, earthy nucleus—probably some other titanium-bearing mineral from which rutile formed.

GALENA: There are a few grains of galena in several of the samples of quartzite. Its cubic grains suggest an authigenic origin, but it may be detrital.

COLLOPHANITE: Collophanite is abundant in two samples (P-20 and P-46). It forms light-brown irregular earthly grains. The heavy fractions containing the mineral gave a strong test for phosphates.

GEOGRAPHIC AND STRATIGRAPHIC RELATIONS

A number of the heavy minerals in the Pokegama quartzite are concentrated in certain geographic areas, and a few are more abundant in certain stratigraphic units of the formation than in others. Furthermore, at places there appears to be a relation between the heavy minerals of the quartzite and those of the older rocks to the north. The following relations are noteworthy:

(1) Anatase and leucoxene are most abundant in the quartzite of the central portion of the range where the granites are relatively high in sphene. In sample P-20 from near a basic border facies of the granite that is high in sphene, over 50 per cent of the heavy fraction is anatase. In the Virginia "Horn" area the pre-Pokegama porphyries and slates are low in titanium minerals, and all quartzite samples from the "Horn" area and from the eastern part of the range have less than 5 per cent of anatase in the heavy accessory minerals.

(2) The quartzite samples containing more than 10 per cent magnetite in the accessory minerals came from outcrops near areas of magnetite-rich granite near Chisholm or Archean greenstone in R. 16 W.

(3) Hornblende is present in the quartzite throughout the entire area. However, the accessory minerals containing more than 25 per cent of hornblende grains came from samples from near the same areas as those rich in magnetite.

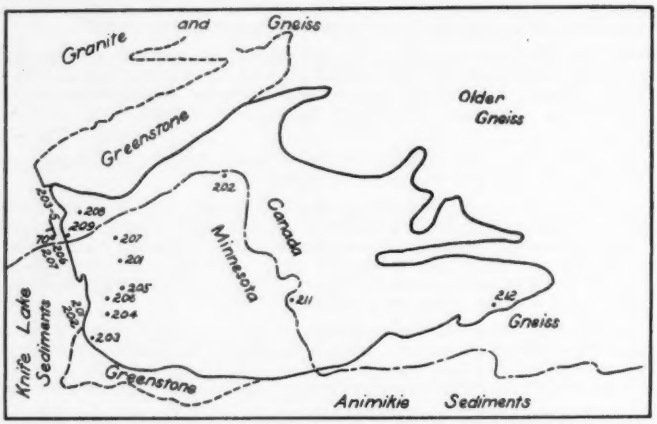

FIGURE 10.—*Map of Saganaga granite and location of samples*
(Area about 35 by 20 miles)

(4) There is apatite in all but seven samples of the quartzite. It is least abundant in the basal part of the formation, where each heavy separate contains less than 5 per cent, and most abundant in the medium- to coarse-grained horizons in the main body of the formation, where a number of the separates contain more than 30 per cent apatite.

(5) In 10 of the 13 samples which contain more than 10 per cent of apatite grains in the heavy residues, hornblende is also abundant, but tourmaline is rare. Since tourmaline is not abundant in the granite, this association of high apatite with hornblende and low tourmaline may indicate a period of deposition when local rocks were contributing a high percentage of the sediment.

(6) There is tourmaline in all textural facies of the formation. It is somewhat less abundant near the top of the quartzite, especially in the areas near the greenstone and near the basic border facies of the granite. It is less abundant in the samples that are high in apatite and hornblende. Most of the tourmaline grains are well rounded and larger than the grains of the other heavy minerals. Toward the east end of the range a high percentage of the tourmaline is in small and prismatic grains. These grains may have had their source in the Lower Huronian slates of that region.

(7) Zircon is somewhat more abundant in the fine slaty facies of the Pokegama than in the massive layers of the main body of the formation. In these finer sediments a high percentage of the zircon is well-rounded hyacinth, whereas in the coarser facies many of the grains are euhedral.

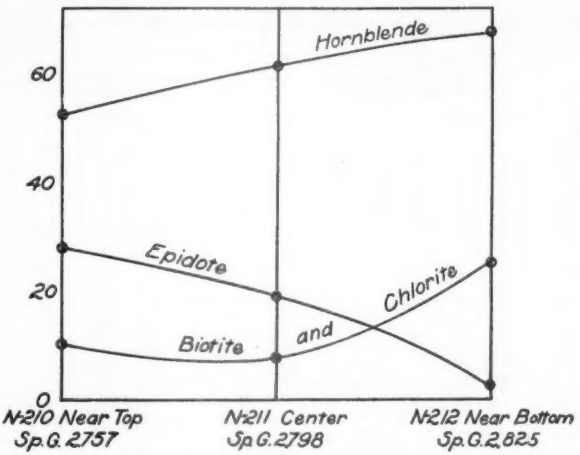

FIGURE 11.—*Differences in heavy minerals with original depth in the Saganaga batholith*

SAGANAGA BATHOLITH

The Saganaga batholith lies partly in Minnesota and partly in Ontario, about 50 miles west of Pigeon Point at the northeast corner of Minnesota. It intrudes the Keewatin greenstone but lies unconformably below the oldest sedimentary series exposed in the region. It is thus a good example of Laurentian, in the sense of the granite older than the sediments.

Granite makes up a high per cent of the Saganaga batholith, and this rock is distinguished from nearly all other granites in the Lake Superior region by its coarse spots of quartz (Pl. 3, fig. 2). It is the chief rock in an area about 15 by 25 miles. The petrography and structure have been described in some detail (Grout, 1929; 1936). There are some slight differences in specific gravity and varietal minerals from the western, upper part, to the eastern, originally deeper parts of the mass (Fig. 11). The borders are at places less quartzose and darker than the main facies. Lamprophyres, pegmatites, and aplites are scattered widely in the area.

Samples were taken chiefly from the upper part of the batholith, as this contributed most to the overlying sediments. Some material in the

sediments clearly came from the wall rocks which are Keewatin greenstone and jaspery iron-bearing rocks. The heavy accessory minerals of the granite are zircon, sphene, apatite, magnetite, ilmenite, and secondary pyrite, hematite, and leucoxene (Table 9). Locally near Gold Island

TABLE 9.—*Heavy minerals of the Saganaga granite, Minnesota and Ontario*

Sample No.	% Heavy mineral in washed sample	Mineral percentage of heavy separates						Percentage of each mineral in heavy accessories						
		Hornblende and Augite	Biotite and Chlorite	Heavy Muscovite	Epidote and Zoisite	Pyrite and Hematite	Accessories	Zircon	Sphene	Apatite	Ilmenite and Leucoxene	Magnetite and Hematite	Fluorite	Others
		Granites												
N–201	4.6	51	22	.....	9	.....	18	2	14	12	30	41	.....	C–Pr. R–1
N–202	15.1	82	8	.....	4	.....	6	3	9	15	59	14	.....	
N–203	7.5	66	10	.....	6	.....	18	1	2	10	39	48	.....	
N–204	9.9	65	9	.....	17	.....	8	3	16	16	31	34	.....	
N–205	5.4	46	26	.....	10	Tr.	18	3	13	13	25	46	.....	
N–207	1.2	1	13	2	3	Pr.	81	Tr.	Tr.	5	33	3	58	C–Tr. U–Pr.
N–208	2.9	5	71	.....	5	1	18	5	4	28	57	4	Pr.	R–Pr. U–1
N–209	2.0	Pr.	54	.....	Pr.	9	36	4	Tr.	21	64	5	Tr.	C–6 U–Pr.
N–210	9.0	56	11	.....	27	Tr.	6	Tr.	19	47	20	14	.....	
N–211	7.2	65	5	.....	20	Pr.	10	5	34	17	6	38	.....	
N–212	14.9	70	23	.....	2	Tr.	5	12	29	53	Tr.	6	.....	
		Granite Boulders of Conglomerate												
P–205A	.5	.....	x	x	.....	x	.....	Pr.	.....	28	17	Tr.	.....	Mu–53 U–1
		Lamprophyre												
N–206	29.0	18	47	Tr.	24	Pr.	10	.....	.....	2	22	75	.....	C–1

C–Carbonate
Mu–Muscovite
R–Rutile
U–Unknown
Tr.–Trace (0.–.49%)
Pr.–Present (.5–.99%)

there are purple fluorite, carbonate altered to iron oxide, and traces of rutile. As might be expected from the dominantly hornblendic nature of the rock, sphene is much more prominent than zircon. No garnet, sillimanite, andalusite, kyanite, brookite, anatase, monazite, xenotine, barite, or topaz has been discovered here. The lamprophyre, sample N-206, shows little but apatite and iron oxide minerals.

The accessory minerals closely resemble those in the Giants range mass. Apatite is chiefly in smaller grains than most of the other heavy minerals. Rutile occurs as brown, fluted prisms. Much of the altered mica has

rutile in sagenite network. Sphene is nearly all purplish brown, but about half of the grains are dusty from alteration. Zircon crystals are hyacinths, with about the same variety of forms as those in the Giants range,

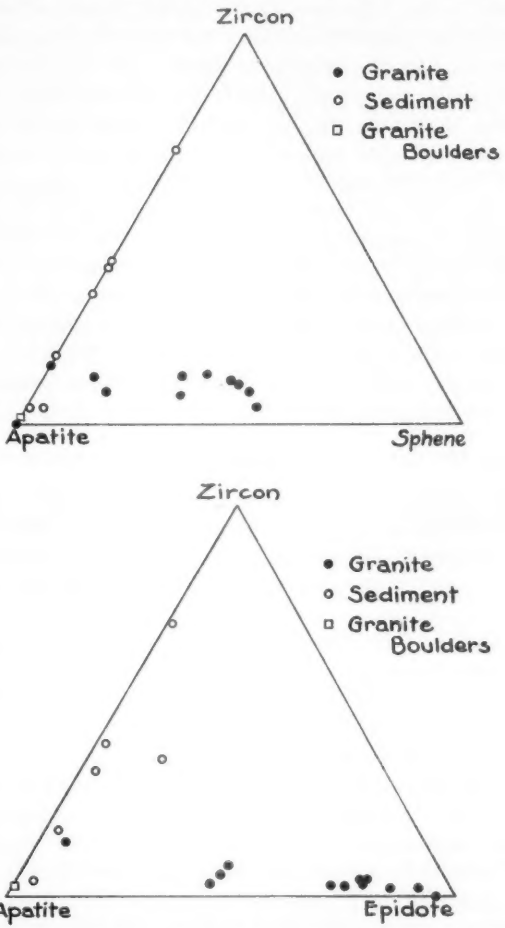

FIGURE 12.—*Changes in ratios of heavy accessory minerals from Saganaga granite to overlying sediments*

but a higher percentage of them are small, short, and almost egg-shaped, with a series of pyramids; only a few are prisms of moderate length. Several have thin red hematite (?) flakes that give them a more brilliant

color. A few large ones have mineral inclusions. Fluorite is mostly blue or purple but grades through very pale tints to colorless; it has many liquid inclusions with movable (dancing) gas bubbles.

In addition to the differences in the varietal heavy minerals in different parts of the granite mass there is a little difference in accessory heavy minerals. In the originally deeper part of the mass N-212 (where hornblende, biotite, and chlorite are more abundant and epidote less abundant than near the top, N-210), apatite is relatively more abundant, and magnetite and leucoxene less abundant than near the top. This is somewhat suggestive of the findings in other masses, where accessories are different near the borders and centers of the masses. There is a lack of regularity in the reports in the literature, however; Marsden reported (Winchell, 1933) that near the borders apatite is low, and sphene and pyrite high compared with the center of the mass; and McAdams reported (1936) that zircon is more abundant than apatite near the base and apatite more than zircon at the top of a mass. Possibly the accessory mineral ratios change in about the same way that ratios of abundant minerals do (Fig. 11).

BASAL KNIFE LAKE SEDIMENTS OF THE SAGANAGA DISTRICT

The heavy minerals of the basal Knife Lake sediments overlying the Saganaga batholith are apatite, carbonates, chlorite, epidote, hematite, leucoxene, muscovite, opaque minerals, pyrite, and zircon. There are also in a few samples anatase, garnet, hornblende, ilmenite, sphene, and tourmaline.

Most of the heavy fractions contained from 10 to 20 per cent of each of the following secondary minerals: carbonates, chlorite, pyrite, hematite, and muscovite. The relative abundance of such constituents is shown in Table 10. They were not counted in determining the percentage distribution of the accessory minerals.

Apatite, the dominant accessory in most of the samples, ranges from 5 to 69 per cent. Leucoxene is abundant as irregular earthy aggregates. Zircon occurs sparingly in each sample. Epidote occurs in most samples and constitutes 84 per cent of the accessory grains in one.

Apatite: Most of the apatite occurs as subangular and subrounded grains. Few are well rounded. Nearly all the grains are transparent and colorless. A few contain brown and opaque inclusions.

Epidote: The epidote occurs as small pale greenish-yellow, irregular and angular grains. The transparent grains are weakly pleochroic. Many of the grains are yellowish and very dusty.

Zircon: Zircon grains range from the coarsest to the finest sizes recovered. However, most of the grains are small. Several varieties were observed that showed a wide range of crystal forms and habits, including excellent examples of twinning.

Most of them are pale pinkish purple or pinkish brown—the hyacinth type. Grains of this variety show crystal outlines, and most of them are finely zoned. Many of the zoned grains are so dusty that the color is obscured. Several of the transparent pinkish grains show a partial border or rim of colorless zircon in the outer zones. Most of the grains of colorless zircon are oval. All varieties contain inclusions.

TABLE 10.—*Heavy minerals of basal Knife Lake sediments*

Saganaga Region

Sample No.	Lithology	Weight % of heavy minerals	Percentage distribution of heavy minerals											
			Relative abundance						Percentage accessories (all others excluded)					
			Muscovite	Hematite	Pyrite	Carbonate	Chlorite	All accessories	Apatite	Epidote	Leucoxene	Opaques	Zircon	Misc.
P201	Conglomerate Jasper and Granite	1.348	...	P	P	P	F	P	9	Tr.	74	8	4	Il–5 U–Pr. Gr.–1
P202	Sandstone	.612	P	P	P	P	F	P	13	5	69	...	9	Gr.–Pr. U–4 T–Pr.
P203	Varved shaly graywacke	1.484	...	P	P	P	P	A	5	84	8	2	1	
P204	Crossbedded sandstone	.371	P	P	F	P	C	P	36	Pr.	38	12	12	An–Pr. T–1
P205a	Boulders of Conglomerate	.534	C	P	C	P	C	C	69	...	19	7	4	U–1
P205b	Sandy matrix of above	.520	P	P	P	P	F	P	57	2	28	9	2	Sph–Pr. U–1
P206	Coarse and fine sand	.275	...	P	A	...	C	C	10	Tr.	51	11	24	Hb–Tr. U–3 An–Pr.
P207	Arkose sand	.459	C	P	C	A	P	P	40	4	34	12	8	Hb–2

Il–Ilmenite
Hb–Hornblende
F–Flood (more than 50%)
A–Abundant (30%–50%)
T–Tourmaline
Gr–Garnet
An–Anatase
Sph–Sphene
C–Common (15%–30%)
P–Present (0%–15%)
Pr.–Present (0.5–0.9%)
Tr.–Trace (0–0.5%)

KEWEENAWAN IGNEOUS ROCKS

GENERAL NOTES

The flows, sills, and dikes of the Keweenawan offer a problem in the study of accessory minerals that is very different from that of the granites. Magnetite and ilmenite are very abundant in the basic rocks, and the flows of different compositions have very different accessory minerals. The fine grain and common oxidation of the flows also confuse the mineral study. Even the material passing the 100-mesh sieve and sinking in the bromoform is largely made up of aggregates of many small grains. Finer grinding liberated some small amounts of heavy accessory minerals even when grinding to 80-mesh or 100-mesh gave over 90 per cent aggregates (samples marked by asterisk in Table 11).

The general distribution and relations of the Keweenawan rocks in Minnesota are covered by earlier reports (Leith, Lund, and Leith, 1935).

Thirty-five samples were taken from the north side of Lake Superior, and 11 (N-336—N-346) from Pine County in east-central Minnesota. The method of sampling was like that in the granites.

The main flood minerals of the heavy separate are augite, hornblende, olivine, biotite (and chlorite), epidote, secondary sericite, and introduced pyrite, carbonate, and zeolites. Some diallage and hypersthene are included with augite in the table.

In the heavy accessory minerals of the Keweenawan igneous rocks magnetite, ilmenite, and their alteration products largely dominate. The statement holds for the basalt and felsite flows and for the intrusive gabbro and "red rock" (granite). There are, in addition, apatite, anatase, fluorite, garnet, sphene, tourmaline, and zircon. Very few grains remain unidentified, and these may include some secondary minerals associated with the zeolites and carbonates. In the group of 46, there are only five rocks in which some accessory mineral other than an iron ore mineral makes over 10 per cent of the heavy accessory group. Table 11 shows the results arranged according to general rock type—31 basalt flows, 6 felsite flows, 8 sills of diabase and related rocks, and 2 intrusive granites, one a "red rock" facies of the basic sills, and one a rather different intrusive, later than the gabbro in Cook County.

ABUNDANT HEAVY MINERALS

AUGITE and related pyroxenes form nearly half of several basalts and diabase but are altered in some to chlorite; they are not prominent in the silicic rocks. Most of the augite is brown to purple or gray. Notably pleochroic hypersthene occurs in the sill, N-326.

BIOTITE is commonly brown or orange but turns green and is altered to chlorite (and leucoxene) in many samples.

CARBONATE is probably mostly a secondary ferruginous calcite.

EPIDOTE, in irregular fragments and dusty aggregates, is mostly greenish-yellow but ranges with composition from brown to colorless.

FELDSPARS appear in some aggregates, where they are attached to or include heavy minerals. They have been noted with inclusions of magnetite, hematite, olivine, and even apatite.

HEMATITE is dusty, red, and largely in coatings or aggregates but partly in grains formed from magnetite or introduced pyrite.

OLIVINE is colorless except where altered to serpentine or iddingsite. It is noted in the heavy fractions only in the coarser diabases such as N-322, N-325, N-326, and N-335. Thin sections of the basalts show only pseudomorphs of olivine. Olivine is reported in Table 11 with the augite.

HORNBLENDE is pale to strong green, and much of it is fibrous and probably formed from augite.

PYRITE appears in a few samples as cubes, striated and bevelled with other forms. A larger number of samples had such coarse pyrite that grinding to 80-mesh left only broken conchoidal surfaces.

ACCESSORY HEAVY MINERALS

ANATASE appears in a few heavy residues as rectangular plates with zonal growth; they are submetallic to opaque gray.

TABLE 11.—*Heavy minerals in some Keweenawan rocks, Minnesota*

Sample No.	% Heavy mineral in washed sample	Mineral percentage of heavy separates									Percentage of each mineral in heavy accessories							
		Aggregates	Pyroxene and Olivene	Biotite and Chlorite	Epidote	Hornblende	Sericite	Pyrite	Carbonate	Accessories	Apatite	Fluorite	Ilmenite and Leucoxene	Magnetite and Hematite	Zircon	Sphene	Garnet	Others
Basalts																		
N-305	35.5	39	Tr.	Tr.	14	....	....	....	....	47	Tr.	....	3	97	....	....	Tr.	
N-307	2.4	9	2	16	....	Tr.	....	Tr.	Pr.	73	Pr.	13	45	39	Tr.	Tr.	Tr.	A–Tr. U–Pr.
N-308	63.0	26	50	4	....	....	....	....	....	20	Tr.	Tr.	31	68	....	....	....	U–Tr.
N-309	46.4	28	31	1	Tr.	Tr.	Pr.	....	Tr.	38	....	....	8	87	....	....	....	U–5
N-310	60.4	15	....	2	....	Tr.	....	Tr.	Tr.	82	Tr.	....	Tr.	99	....	Tr.	....	U–Tr.
*N-311	18.7	73	....	Tr.	....	....	....	Tr.	Tr.	27	1	....	80	19	....	....	....	U–Tr.
*N-313	49.8	35	Tr.	Tr.	Pr.	31	....	Tr.	Tr.	33	Tr.	....	Tr.	99	Tr.	....	1	U–Tr.
*N-314	47.7	82	....	1	3	9	....	Tr.	Tr.	4	33	Tr.	10	57	Tr.	....	Tr.	R–Tr. U–Tr.
*N-319	40.6	41	Tr.	Tr.	2	4	....	Tr.	....	53	Tr.	....	1	98	Tr.	....	Tr.	U–Tr.
*N-320	48.8	....	Pr.	1	3	Pr.	....	Tr.	Tr.	95	Tr.	....	1	98	?	?	Tr.	A–Tr. U–Tr.
N-323	75.6	84	Tr.	Tr.	Tr.	10	Tr.	Tr.	....	5	Tr.	....	3	97	....	....	Tr.	U–Tr.
N-324	37.2	85	....	2	Pr.	8	Tr.	....	Tr.	5	....	....	Pr.	99	....	....	Tr.	
N-327	68.8	55	....	10	Pr.	30	Tr.	Tr.	....	5	Tr.	....	3	96	....	....	....	U–Tr.
N-328	46.7	74	....	6	16	Tr.	....	....	Tr.	4	....	....	Pr.	99	....	....	....	
*N-329	34.5	....	3	1	20	Pr.	....	Tr.	....	74	Tr.	....	Pr.	93	Tr.	....	1	
N-330	52.0	....	72	Pr.	....	....	....	....	....	28	....	....	1	99	....	....	....	U–Tr.
N-331	57.4	....	91	Tr.	....	Tr.	....	....	....	9	Tr.	....	Pr.	99	....	....	....	
*N-332	7.8	33	Tr.	Tr.	1	....	....	Tr.	....	65	....	....	70	30	....	....	....	U–Tr.
N-333	55.1	2	60	Tr.	Tr.	....	....	....	....	37	....	....	3	97	....	....	....	
N-334	39.4	6	51	Tr.	Pr.	....	....	....	....	43	Tr.	....	23	77	....	....	....	
N-336	39.7	16	55	8	Pr.	....	....	....	....	20	Tr.	....	14	86	....	....	....	
N-337	36.9	4	67	1	Tr.	....	....	....	....	28	....	....	45	55	....	....	....	
N-338	36.6	16	41	1	Tr.	....	....	....	....	41	....	....	5	95	....	....	....	
N-339	9.7	21	Pr.	Tr.	Tr.	....	....	....	Tr.	78	Tr.	....	4	96	Tr.	....	....	
N-340	21.2	15	59	2	Tr.	....	....	....	....	24	Tr.	....	84	16	....	....	....	
N-341	46.3	12	46	Tr.	....	....	....	....	....	41	....	....	18	82	....	....	....	
N-342	54.0	4	71	Pr.	Tr.	Tr.	....	....	....	24	Tr.	....	8	92	....	....	....	
N-343	18.7	76	Pr.	Tr.	Tr.	....	....	....	Tr.	23	Tr?	....	100	Tr.	....	....	Tr.	
N-344	50.9	22	44	1	....	....	....	....	....	33	Tr.	Tr.	23	77	....	....	....	
N-345	34.0	58	17	Tr.	....	....	....	Tr.	....	25	Tr.	....	59	41	....	....	....	U–Tr.
N-346	52.8	84	6	Tr.	2	Tr.	....	....	....	8	Tr.	....	99	Pr.	....	....	....	
Felsites																		
N-302	5.6	82	Tr.	2	....	....	....	Tr.	Tr.	15	2	....	96	2	Tr.	Tr.	....	U–Tr.
N-304	1.4	81	2	Tr.	Tr.	Pr.	....	Tr.	Tr.	16	1	10	49	27	9	....	....	A–Pr. U–Tr.
N-306	58.5	15	57	Tr.	1	....	....	....	Tr.	27	....	....	17	83	....	....	....	
N-312	1.1	8	2	24	Tr.	Tr.	....	2	Tr.	63	Pr.	3	53	36	2	3	....	A–Tr. T–Tr. U–2
*N-315	1.1	47	Tr.	Tr.	3	Tr.	....	2	Tr.	47	1	Tr.	67	22	7	....	1	U–Tr.
N-318	19.4	29	....	Pr.	1	4	....	Tr.	Tr.	66	1	....	Tr.	97	2	Tr.	Tr.	U–Tr.
Diabases and Gabbros																		
N-303	41.3	....	62	5	1	10	....	Tr.	....	22	9	....	57	30	....	....	....	U–4
N-316	21.5	7	23	10	Tr.	46	....	Tr.	....	14	2	....	64	31	2	Tr.	....	U–Tr.
N-317	28.2	28	11	11	2	40	Tr.	....	....	8	Tr.	....	....	99	Tr.	....	....	U–Tr.
N-321	39.1	8	34	9	5	7	....	Pr.	Tr.	37	2	....	9	89	....	Tr.	....	U–Tr.
N-322	42.5	Tr.	66	1	5	Tr.	....	....	Tr.	27	2	....	35	63	Tr.	....	....	U–Tr.
N-325	33.0	....	87	3	Tr.	Tr.	....	....	....	10	4	....	20	76	....	....	....	
N-326	31.6	Tr.	35	18	2	17	Tr.	Tr.	....	27	8	....	31	58	Tr.	....	....	U–3
N-335	36.0	....	89	4	Tr.	....	....	....	....	7	Tr.	....	35	62	....	....	....	U–3
Granites																		
N-301	8.7	....	....	42	Tr.	Pr.	....	Tr.	Pr.	58	11	....	34	52	Tr.	2	....	U–Pr.
N-350	15.9	2	Tr.	4	2	78	....	Tr.	Tr.	13	3	1	60	27	2	7	....	U–Tr.

U–Unknown T–Tourmaline * Ground to 200 mesh. (others 80 mesh.) Tr.–Trace (.0 to .49%)
A–Anatase R–Rutile Pr.–Present (.50 to .99%)

APATITE is the most abundant accessory aside from iron minerals in the basalts and in some diabases. It ranges widely in size, from grains in feldspar, through euhedral prisms, to large broken fragments that show little sign of their original forms. The euhedral grains are short prisms with several terminal faces, but many longer euhedral grains must have been in the rock to furnish the very abundant fragments. Most of the grains are colorless, but many have yellow, brown, and gray tints.

FLUORITE is more abundant in the felsite flows than was suspected from hand specimen examination. It ranges from colorless to blue and purple.

GARNET is not at all common but it occurs in several samples. In one or two it is pink and quite like common garnets of granites, but in one rock it is more yellow, and in another it is so dusty with hematite that its identification is a little uncertain.

ILMENITE is common in the less magnetic fractions and shows the usual alteration to LEUCOXENE.

MAGNETITE is mostly in irregular fragments of crystals, but some small grains are octahedral.

RUTILE and TOURMALINE were each seen in but a single grain in the work on Keweenawan igneous rocks of Minnesota. Tourmaline is pleochroic in brown tints, in a prism, with terminal faces at one end. The rutile is a darker brown irregular fragment, with a metallic reflection in one position.

SPHENE occurs in small amounts in the more silicic rocks.

ZIRCONS are to be expected in silicic rocks but occur in a variety of Keweenawan rocks. They range from colorless to pale brown, yellow brown, and a few are stained red by hematite. Inclusions are common in the large grains as needles or needle-like cavities. Crystals are common, but not all are perfect. They range from short grains with nearly round ends to long needles, and they show prisms of two orders and at least two bipyramids. Common forms in the Keweenawan of Minnesota, which this work has not revealed in older igneous rocks, are the clear simple square prisms with bipyramids of the same order. This is the "normal" Keweenawan type (Pl. 2, fig. 3).

KEWEENAWAN AND RELATED SEDIMENTS

LOWER KEWEENAWAN

The earliest Keweenawan sediments exposed in northeastern Minnesota rest unconformably on folded Huronian slates and under slightly tilted lava flows. Southwest of Duluth these basal Keweenawan beds are exposed in sec. 20, T. 49 N., R. 15 W., and in sec. 1, T. 48 N., R. 16 W., near Fond du Lac, where they are composed of quartzose conglomerate and firmly cemented sandstone. At Fond du Lac a white quartz conglomerate is overlain by red sandstone and conglomerate that contains basalt pebbles.

The chief heavy minerals of the basal beds in sec. 20, T. 49 N., R. 15 W., are, in order of abundance, earthy aggregates of altered ferromagnesian minerals, leucoxene, apatite, hornblende, zircon, and garnet. The earthy aggregates constitute about 90 per cent of the heavy fractions. Apatite is the most abundant accessory mineral. Hornblende is common, and zircon and garnet are rare. The zircons show a variety of sizes and of colors. Some grains are short, stubby, rounded, and nearly colorless, others pale yellowish-brown.

SEDIMENTS INTERBEDDED WITH FLOWS

Pine City.—Thin beds of sandstone and conglomerate occur interbedded with the Keweenawan flows along the Snake River east of Pine City, Minnesota. The outcrops are deeply weathered and infiltrated with iron oxide. The pebbles in the conglomerates are mainly altered basic igneous rocks. They range in size from a quarter of an inch to over 2 feet in diameter. The larger pebbles were avoided in sampling.

Since the formations are much altered, many of the original accessory minerals are attacked. Reddish chlorite, brownish leucoxene, and opaque minerals predominate in the heavy fractions. Only a few grains of apatite and zircon were observed. Taken jointly they constitute less than 5 per cent of the total heavy fractions. A few of the zircons are pale-brown simple prisms and bipyramids like the crystals in igneous rocks of the Keweenawan, and not in older rocks.

North Shore of Lake Superior.—Along the north shore of Lake Superior, wave action has exposed a number of thin beds of grayish-green sandstone, interbedded with the basalt flows. These sandstones are exceptionally high in heavy minerals. Approximately 50 per cent of each sample is composed of material with a density greater than that of bromoform. About 98 per cent of the heavy fraction is a semitransparent greenish mineral that resembles dusty epidote or chlorite. The remaining 2 per cent is composed of grains of apatite, zircon, and pink garnet. The original character of the zircon grains is concealed by a dusty alteration product.

RED CLASTIC SERIES

The term Red Clastic series is used by the Minnesota Geological Survey for a series of alternating red shales and arkosic sandstones that crop out along the St. Louis River southwest of Duluth and along the Snake River north of Mora. The extent of the formation is not definitely known, but it has been penetrated by a number of deep wells which indicate that it is continuous southward in the granitic pre-Cambrian trough that extends from these outcrops south through east-central and southeastern Minnesota. The thickness of the series varies with the irregularities of the upper surface of the granite and basalt over which it was deposited. Deep wells show that at Stillwater its thickness is 2458 feet, at Minneapolis 1012 feet, at Mankato 1289 feet, and at Rochester 2033 feet. East of Rochester it thins rapidly, and at Winona a number of deep wells penetrated no Red Clastic series; there the early St. Croixan sediments rest directly on pre-Cambrian granite.

Fifteen samples were collected from outcrops of the Red Clastic series along the St. Louis river near Fond du Lac (Fig. 14). The lithological

TABLE 12.—*Heavy minerals of the Red Clastic series*

Fond du Lac

Sample number and location of sample	Weight % of heavy minerals		Relative abundance before acid treatment				Percentage distribution of heavy minerals					
	Before HCl Treatment	After HCl Treatment	Carbonate	Earthy Aggs. Mainly Leucoxene	Pyrite	All accessories	Apatite	Garnet	Zircon	Tourmaline	Opaques	Miscellaneous
Mission Creek—Quarry												
P402	3.0	2.2	P	A	P	C	56	Pr.	20	17	3	Hb.–Pr. U–3
P403	1.5	1.1	P	F	P	A	51	9	19	16	2	U–2
P404	1.3	1.1	P	A	P	C	48	7	16	23	4	U–1
P405	0.6	0.3	P	A	P	C	50	7	13	23	4	Hb.–Pr. U–2
R. R. Cut N. Chambers Grove												
P406	2.1	1.9	P	A	.....	A	48	7	13	17	9	U–4
P407	2.1	1.8	C	A	.....	A	54	3	10	24	6	Bi.–Pr. U–4
P408	3.6	2.3	P	C	P	C	30	2	10	11	45	U–2
P409	2.6	2.0	P	A	P	C	52	5	19	17	5	Ep.–Pr. U–3
P410	.....	.....	F	C	.....	C	53	2	13	19	5	Bi.–4
Old Quarry W. Bank St. Louis River												
P411	2.1	1.6	P	A	.....	A	63	2	13	9	3	Bi.–6 U–3
P412	1.8	1.4	P	C	P	A	60	2	14	8	13	Rt.–Pr. U–4
P413	1.2	0.9	P	F	P	C	40	6	17	29	2	Rt.–1 U–5
P414	0.4	0.2	P	A	P	C	42	6	26	21	3	Rt.–Pr. U–2
Old Quarry Chambers Grove												
P415	2.4	1.8	C	A	.....	A	49	4	15	11	18	Bi.–Pr. U–3
P416	2.2	1.7	P	A	.....	A	58	2	12	19	7	Rt.–Tr. U–2
One Mile N. of Mora												
P448	.3	.2	P	F	.....	A	5	2	17	9	52	Rt.–14

F=More than 50%
A=30–50%
C=15–30%
P=0–15%

Pr.–Present (0.5–0.9%)
Tr.–Trace–less than 0.5%

Hb.–Hornblende
Bi.–Biotite
Ep.–Epidote
Rt.–Rutile

characteristics and locations of the samples are indicated in the columnar sections in Figures 15, 16, and 17.

The heavy minerals of the Red Clastic series are apatite, biotite, carbonate, garnet, hornblende, ilmenite, leucoxene, magnetite, pyrite,

tourmaline, and zircon. Other minerals that appeared in only a few samples are epidote and rutile. Only a few grains remained unidentified, and their percentage of the total is shown in Table 12. Some of the heavy fractions contained floods of carbonates, earthy aggregates of altered chlorite and leucoxene, and pyrite. The relative abundance of

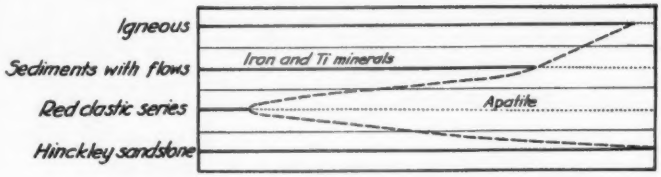

FIGURE 13.—*Ratios of apatite to the sum of magnetite, ilmenite, and leucoxene in Keweenawan igneous rocks and sediments*

such constituents also is shown in Table 12. They were not counted in determining the percentage distribution of accessory minerals.

The total percentage by weight of the heavy fractions, including the earthy aggregates, is not so great as might be expected from ferruginous sediments. The greatest is 3.6 per cent, and the smallest 0.4 per cent. Apatite dominated in all but one sample in which opaque minerals made up 45 per cent of the accessory minerals. In 10 samples apatite grains composed more than 50 per cent of the accessory minerals, and the range is from 30 to 63 per cent. Tourmaline was present in all samples, ranging from 8 to 29 per cent. Zircon ranges from 10 to 26 per cent and garnet from 0.5 to 9 per cent.

APATITE: Apatite occurs as large, colorless, rounded prismatic grains. Many contain pale-brown to opaque inclusions some of which are euhedral in outline; others are minute, irregular particles. Some samples contain many small euhedral grains of apatite as well as large rounded grains. In sample P-410 the small grains predominate.

GARNET: Garnet occurs as colorless, pink, and brownish-red grains. Some of the larger grains show smooth parting surfaces, but most of the surfaces are rough and irregular. Many of the grains are feebly anisotropic.

TOURMALINE: The tourmaline is mainly brown to brownish black, but a few grains are deep blue or bluish gray. The larger grains of all color varieties are oval or rounded, whereas many of the smaller grains are subangular. No secondary growth was observed.

ZIRCON: Small zircon grains occur in all the samples of the formation. Most of the grain are less than $\frac{1}{16}$ mm. in diameter. Many elongated grains that appear smooth and rounded over most of their surfaces are, nevertheless, angular and jagged at one end. Such grains may have been broken during crushing. Most of the grains are well rounded and oval in outline. A few long, needlelike crystals with distinct terminal faces were observed. The mineral ranges from the "normal" Keweenawan type to pale brown and light purplish pink. Some of the grains are uniformly zoned. Inclusions are not abundant.

HINCKLEY SANDSTONE

The Hinckley formation is a salmon-colored, medium-to coarse-grained, poorly sorted sandstone. Some beds are arkosic, and some are conglom-

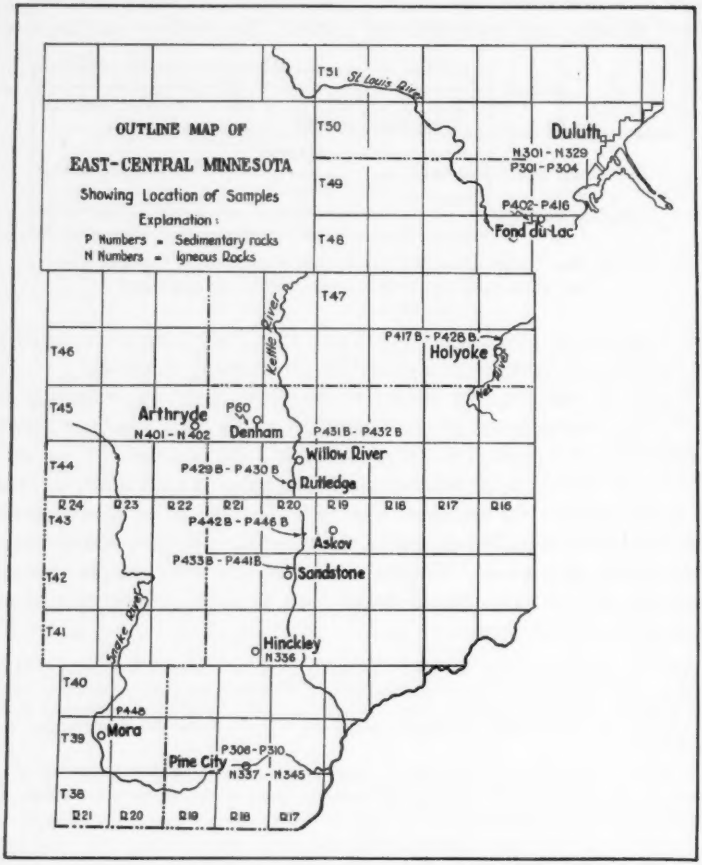

FIGURE 14.—*Outline map showing locations at which certain Keweenawan samples were taken*

eratic, but most of the rock is nearly pure quartz sandstone. The sandstone received its name from the rock once quarried in the bank of the Whetstone River at Hinckley. The formation occurs below the glacial drift in east-central Minnesota in an elongate belt extending from the Nemadji River in Carlton County at the northeast to Wright County at

the southwest. To the south and to the east of Wright County it is overlain by younger sedimentary rocks. Drill cuttings indicate that it occurs as far south as Mankato and Rochester. North and south of the city of Sandstone, Minnesota, the Kettle River has cut a great gorge in the formation. Quarrying operations near the city of Sandstone have exposed a continuous vertical section of approximately 100 feet. The formation dips southeastward at an angle of about 3 degrees.

Thirty samples were collected from outcrops of the Hinckley sandstone. The geographic distribution of the samples is shown on the outline map of Figure 14, and the stratigraphic position of some in the columnar sections in Figures 18 and 19.

The chief heavy minerals of the Hinckley sandstone are anatase, epidote, leucoxene, rutile, tourmaline, zircon, and opaque minerals. Other minerals that appeared in only a few samples are garnet, hornblende, pyrite, and tremolite (Table 13). Garnet was found in two samples only, whereas it occurs in all the samples of the Red Clastic series.

The total percentage of the heavy minerals is very small, from 0.010 to 0.327 per cent. The accessory minerals constitute less than 0.1 per cent in 27 of the 30 samples.

Zircon dominates the heavy minerals in most of the samples, ranging from 18 to 66 per cent. Opaque minerals are most abundant in 5 of the 12 samples from the Net River sections and they are fairly abundant in the Askov section. These sections are stratigraphically lower than the section exposed in the quarry at Sandstone.

Tourmaline is the most abundant heavy mineral in only one sample. The distribution of tourmaline in the other samples is very uniform and averages approximately 12 per cent. Leucoxene occurs in all the samples, ranging from 12 to 29 per cent of the heavy minerals.

In general the physical and optical characteristics of the accessory minerals in the Hinckley sandstone are very similar to those of the Red Clastics series. Outstanding differences exist, however, in the types of zircon grains and in the percentage distribution of the various minerals. The order of their abundance is as follows:

Red Clastic series	*Hinckley sandstone*
1. Leucoxene aggregates	Zircon
2. Apatite	Leucoxene
3. Tourmaline	Tourmaline
4. Zircon	Opaque ores
5. Opaque ores	Garnet (very little)
6. Garnet	(No apatite observed)

The most conspicuous differences are that apatite is absent and garnet very rare in the Hinckley sandstone. Leucoxene is common throughout

TABLE 13.—*Heavy minerals of the Hinckley sandstone*

Geographic and stratigraphic location of samples		Weight per cent of heavy minerals	Percentage distribution of heavy minerals								
Sample number	Thickness (Feet)		Zircon	Tourmaline	Magnetite and Ilmenite	Leucoxene	Rutile	Anatase	Epidote and Zoisite	Unknown	Miscellaneous
Sandstone, Minn.											
Top											
P433B	10	.022	55	15	1	24	Tr.	2	2	.....	Hb.–Tr.
P434B	10	.039	55	11	Pr.	26	.....	4	3	.....	G–Tr.
P435B	10	.027	64	11	2	17	.....	2	Tr.	3	Tm.–1
P436B	10	.049	50	8	.....	29	4	7	2	.....	Hb.–Tr.
P437B	10	.023	54	16	Tr.	23	1	2	1	.....	Py.–2
P438B	10	.029	63	12	Tr.	18	2	2	3	Tr.	
P439B	10	.010	51	15	2	22	Pr.	3	5	Tr.	
P440B	10	.013	47	13	2	34	Tr.	Tr.	3	Tr.	
P441B	10	.038	64	8	1	22	2	2	.....	1	
Askov, Minn.											
Top											
P442B	6	.029	32	12	30	22	.....	1	2	.....	
P443B	6	.019	35	19	23	15	1	1	4	1	Py.–Pr.
P444B	6	.073	47	4	27	17	2	2	.....	2	Py.–Tr.
P445B	6	.015	39	17	20	20	Pr.	4	.....	Tr.	
P446B	6	.031	56	12	10	18	Tr.	Pr.	.....	1	Hb.–1
Rutledge, Minn.											
Top											
P429B	10	.042	66	8	2	16	6	1	.....	1	
P430B	10	.078	56	14	4	17	2	2	2	1	Py.–1
Willow River, Minn.											
Top											
P431B	10	.023	28	40	Pr.	27	.....	1	1	.....	Py.–1
P432B	10	.024	48	23	2	22	Pr.	2	2	Tr.	
Net River, Minn.											
Top											
P417B	6	.034	37	16	12	27	1	3	2	.....	Py.–1
P418B	5	.045	45	15	16	18	4	2	.....	Tr.	
P419B	4	.021	18	14	35	28	3	.....	.....	2	Py.–1 Hb.–Tr.
P420B	7	.067	31	14	30	19	3	.....	1	2	
P421B	10	.045	20	11	47	16	Tr.	5	.....	.....	G–Tr. Hb.–Tr.
P422B	4	.036	26	7	47	15	3	1	.....	Tr.	
P423B	5	.108	27	13	44	12	1	1	1	Tr.	
P424B	6	.077	35	13	30	19	1	1	.....	.....	Py.–Tr.
P425B	6	.086	28	13	37	18	1	3	.....	Tr.	
P426B	8	.074	33	11	39	12	2	3	Pr.	.....	
P427B	7	.146	32	11	26	23	1	6	1	.....	
P428B	5	.327	24	10	42	13	1	7	Pr.	Tr.	Py.–1

G–Garnet, Hb.–Hornblende, Tm.–Tremolite, Py.–Pyrite

Pr.–Present 0.5–0.9%
Tr.–Trace—less than 0.5%.

the Hinckley, but the floods of earthy aggregates that characterize the heavy fractions of the Red Clastic series were not observed in any of the Hinckley samples.

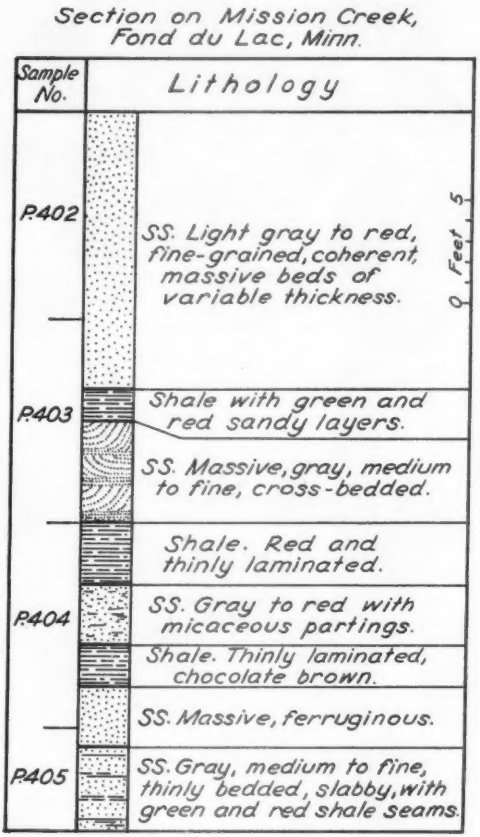
Section on Mission Creek, Fond du Lac, Minn.
Sample No.
Lithology
P-402
SS. Light gray to red, fine-grained, coherent, massive beds of variable thickness.
0 Feet 5
P-403
Shale with green and red sandy layers.
SS. Massive, gray, medium to fine, cross-bedded.
Shale. Red and thinly laminated.
P-404
SS. Gray to red with micaceous partings.
Shale. Thinly laminated, chocolate brown.
SS. Massive, ferruginous.
P-405
SS. Gray, medium to fine, thinly bedded, slabby, with green and red shale seams.

FIGURE 15.—*Section of Red Clastic series at Fond du Lac, showing sources of samples P-402 to P-405*

Zircon grains from the two formations are shown in Plate 4. The zircon in the Hinckley sandstone is coarser grained and more uniformly rounded than that of the Red Clastic series. Yellow-brown, "normal" Keweenawan and hyacinth grains predominate.

STRATIGRAPHY OF THE RED CLASTIC AND HINCKLEY BEDS

The stratigraphic positions of the Hinckley sandstone and of the Red Clastic series in the Keweenawan have not been established. Atwater

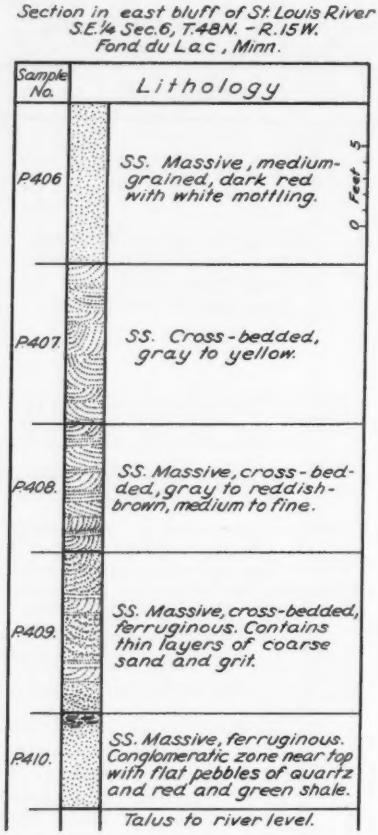
Section in east bluff of St. Louis River
S.E.¼ Sec. 6, T. 48 N. - R. 15 W.
Fond du Lac, Minn.
Sample No.
Lithology
P-406
SS. Massive, medium-grained, dark red with white mottling.
0 Feet 5
P-407
SS. Cross-bedded, gray to yellow.
P-408.
SS. Massive, cross-bedded, gray to reddish-brown, medium to fine.
P-409.
SS. Massive, cross-bedded, ferruginous. Contains thin layers of coarse sand and grit.
P-410.
SS. Massive, ferruginous. Conglomeratic zone near top with flat pebbles of quartz and red and green shale.
Talus to river level.

FIGURE 16.—*Section of Red Clastic series at Fond du Lac, showing sources of samples P-408 to P-410*

(1935, p. 1681) correlated the Hinckley sandstone with the Orienta formation of the Bayfield group and the Red Clastic series with the Amnicon formation of the Oronto group. The evidence on which the correlation was based was not given. By comparing the accessory min-

FIGURE 1. FROM THE HINCKLEY SANDSTONE

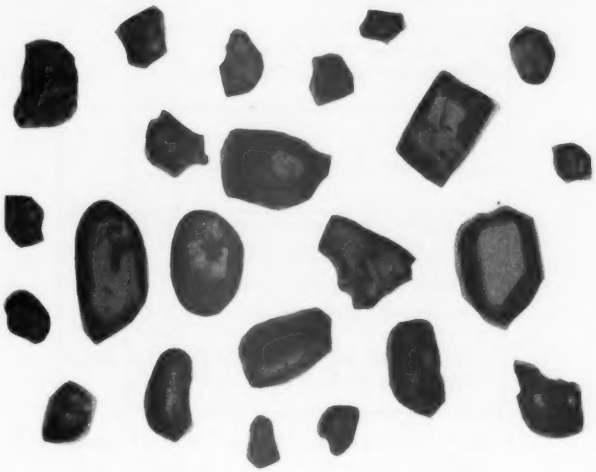

FIGURE 2. FROM THE RED CLASTIC SERIES

ZIRCONS FROM TWO MINNESOTA SANDSTONES (X 125)

STRATIGRAPHY OF THE RED CLASTIC AND HINCKLEY BEDS

The stratigraphic positions of the Hinckley sandstone and of the Red Clastic series in the Keweenawan have not been established. Atwater

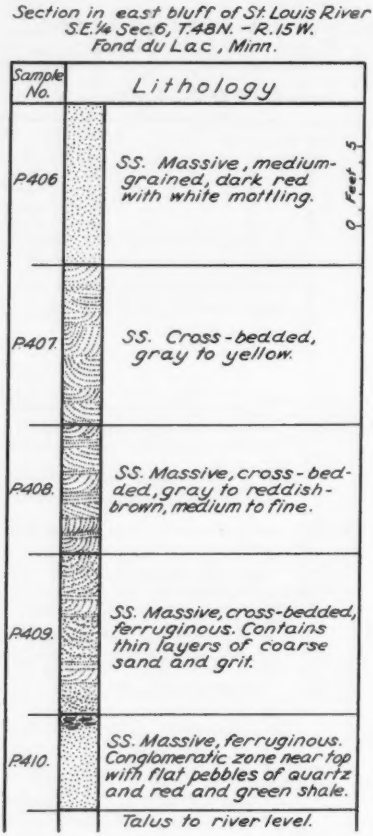
Section in east bluff of St. Louis River
S.E.¼ Sec. 6, T. 48N. – R. 15W.
Fond du Lac, Minn.
Sample No.
Lithology
P406
SS. Massive, medium-grained, dark red with white mottling.
9 Feet 5
P407
SS. Cross-bedded, gray to yellow.
P408.
SS. Massive, cross-bedded, gray to reddish-brown, medium to fine.
P409.
SS. Massive, cross-bedded, ferruginous. Contains thin layers of coarse sand and grit.
P410.
SS. Massive, ferruginous. Conglomeratic zone near top with flat pebbles of quartz and red and green shale.
Talus to river level.

FIGURE 16.—*Section of Red Clastic series at Fond du Lac, showing sources of samples P-408 to P-410*

(1935, p. 1681) correlated the Hinckley sandstone with the Orienta formation of the Bayfield group and the Red Clastic series with the Amnicon formation of the Oronto group. The evidence on which the correlation was based was not given. By comparing the accessory min-

FIGURE 1. FROM THE HINCKLEY SANDSTONE

FIGURE 2. FROM THE RED CLASTIC SERIES

ZIRCONS FROM TWO MINNESOTA SANDSTONES (X 125)

erals of the Hinckley sandstone with those of the various members of the Lake Superior sandstone as reported in Table 6 of this study, it will be noted that the Devil's Island sandstone of the Bayfield group has a

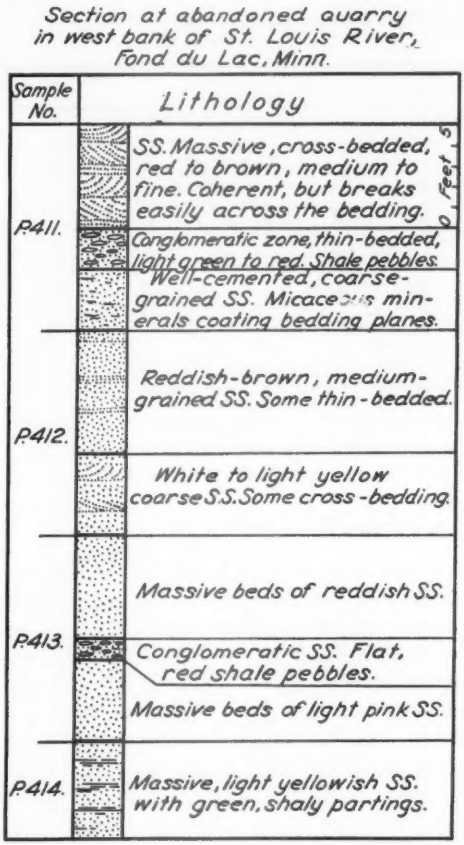
Section at abandoned quarry in west bank of St. Louis River, Fond du Lac, Minn.
Sample No.
Lithology
SS. Massive, cross-bedded, red to brown, medium to fine. Coherent, but breaks easily across the bedding.
0 Feet 5
P.411.
Conglomeratic zone, thin-bedded, light green to red. Shale pebbles.
Well-cemented, coarse-grained SS. Micaceous minerals coating bedding planes.
Reddish-brown, medium-grained SS. Some thin-bedded.
P.412.
White to light yellow coarse S.S. Some cross-bedding.
Massive beds of reddish SS.
P.413.
Conglomeratic SS. Flat, red shale pebbles.
Massive beds of light pink SS.
P.414.
Massive, light yellowish SS. with green, shaly partings.

FIGURE 17.—*Section of Red Clastic series at Fond du Lac, showing sources of samples P-411 to P-414*

very similar mineral assemblage. Both contain very little garnet and no apatite. Zircon and tourmaline are the dominant accessory minerals in each. Likewise the accessory minerals of the Red Clastic series and those of the lower part of the Orienta formation show similarities in mineral species. These similarities suggest that upper Keweenawan sedi-

mentation continued southwest of Lake Superior in Minnesota during the time the Devil's Island sandstone was being deposited. No sandstone equivalent to the Chequamegon sandstone, the uppermost member of the Lake Superior sandstone series, has been reported in Minnesota. If it was deposited, it has been removed by erosion.

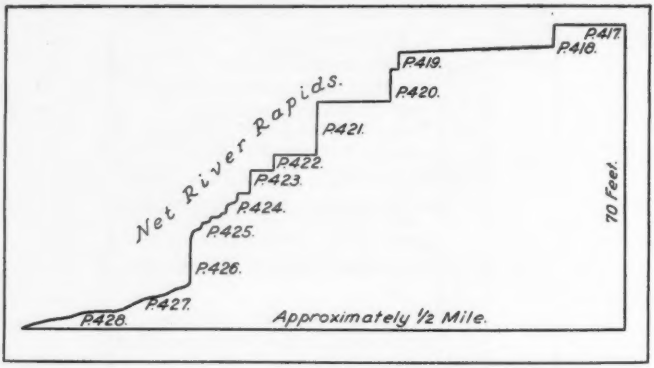

FIGURE 18.—*Section of Hinckley sandstone on Net River, showing sources of samples P-417 to P-428*

SCATTERED GRANITES IN MINNESOTA

Much material from other granites is available in specimens, not all so carefully selected as the samples collected for accessory mineral study. They serve, however, to give a preliminary test of the ages of various masses by correlation based on the three varieties of zircon distinguished in Wisconsin. None of the granites available, from Rainy Lake at the north to Morton and Ortonville at the southwest, showed any zircons of the Keweenawan or "normal" type, though several have been provisionally referred to that age by field studies in poorly exposed areas (Van Hise and Leith, 1911, p. 215). Of 22 samples, 13 had hyacinth and may be assigned tentatively to the Algoman or Laurentian. They may prove very significant in correlation of the sediments injected by the granites.

In eight samples of Vermilion granite, four gave so few zircons that the classification was not attempted, one had clearly hyacinth grains, and the others were not so characteristic—partly brown to colorless, and in one rock possibly malacon.

Two granite samples from St. Cloud, one red and one pink, each showed dominantly hyacinth.

Three samples of gray St. Cloud granodiorite each showed dominantly hyacinth.

Two samples of Rockville granite showed zircons with the forms of

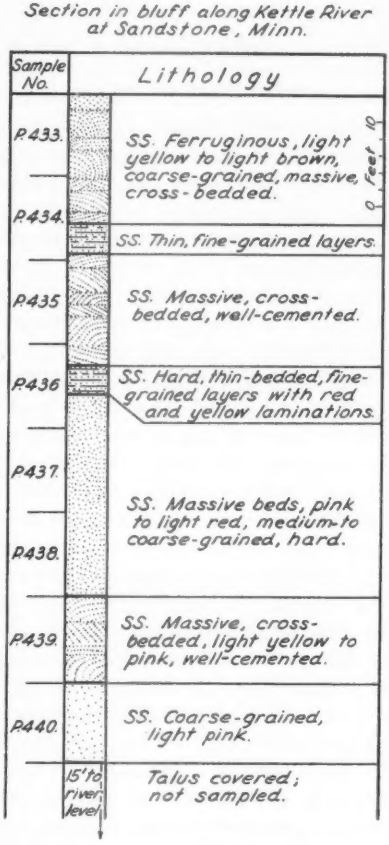

FIGURE 19.—*Section of Hinckley sandstone at Sandstone, showing sources of samples P-433 to P-440*

hyacinth and a very pale pink color probably referable to the same type.

Near the Cuyuna range four granite masses were tested and all showed hyacinth. They are from the Warman Creek quarry and the Isle quarry, and from two outcrops, one of which is 2 miles west and the other 8 miles

east of Dad's Corner, sec. 1, T. 44 N., R. 24 W., and sec. 35, T. 45 N., R. 22 W.

In the Minnesota River Valley the gneiss quarried at Morton furnished hyacinth, but that from Ortonville gave so little zircon that it was not possible to classify it.

DISCUSSION

DISCUSSION OF DATA

Several features of the data presented are in the nature of direct conclusions as to the local relations and correlation of rocks. These are not repeated here. Other data have more general application and they are here summarized and compared with data from other districts to show whether they support or contradict the theoretical concepts and assumptions in heavy mineral studies.

(1). The accessory minerals of a single igneous mass are not usually the same in total or relative amounts in all parts of the mass. The groups working in the Lake Superior region agreed on this before the end of the first season. The data appear in Tables 2 and 3 (Wisconsin and Michigan igneous rocks), Table 7 (Giants range), and Table 9 (Saganaga).

The exact amounts of heavy accessory minerals in a single sample of a single igneous mass have probably never been accurately determined because the methods used result in losses (Tyler and Marsden, 1937, p. 4-16) and because the more abundant heavy minerals can rarely be separated completely from the accessory minerals. The results appear to be sufficiently accurate, however, to say that the amounts are not the same in all parts of a mass. A definite tendency for certain accessory minerals to migrate differentially to the top, bottom, or sides of a magma has been suggested, but more data are needed before conclusions are safe.

The question as to how widely the accessory minerals range in amount (total or relative) in a single intrusion requires more careful discussion. A matter of judgment is involved. When two men inspect a table of results, one says it is a "uniform" or "constant" assemblage or that it shows a "surprising lack of variety," and another, noticing one or two exceptional results in a series of perhaps a dozen, concludes that these destroy the uniformity or constancy claimed by the first. It is better to give actual data rather than refer to uniformity or constancy. Mathematical methods of reporting the degree of similarity may well be applied if there is doubt or disagreement (Dryden, 1935).

After a moderate amount of work on the accessory minerals of igneous masses, some students have concluded that there was at least a limited range in the ratios of certain minerals (Stark and Barnes, 1935). The ratios of zircon, apatite, and sphene are considered most generally appli-

cable to the study of granites. It seems probable that the conclusions were based on too small a set of samples. Several tests are now on record as to the relative quantities of such primary accessories as zircon, apatite, and sphene in other districts. The results are shown by Figure 20. These indicate a wide range in the ratios of the three minerals. The diagrams that show a restricted range appear to be either small masses or large masses that have not been sufficiently sampled. Other minerals might be selected as a basis for comparison but data are not available from many districts. In the Giants range the opaque iron minerals range from 100 per cent magnetite to 100 per cent ilmenite. The variety for other minerals is probably as large as shown in Figure 8. The "constancy" of ratios or accessories within a mass can no longer be said to be a "basic principle of accessory mineral work" (Marsden, 1935). If a constancy or limited range is found, as it appeared in the work of Stark and Barnes on the masses in Colorado, the work should be carefully checked by many more samples before important conclusions are based on the data. This is in no way contradictory to conclusion (4) that certain peculiarities of an accessory mineral may occur in all parts of an intrusion where the accessory mineral is present even in traces.

From the data at hand one should not expect or assume that the relative percentages or actual amounts of the accessory minerals will remain constant through an intrusive. The "index figure"—total percentage of heavy minerals in a rock—(Groves, 1930) suggested by Brammall is probably not of general value in correlation. Even the "index" based on accessory minerals (Wright, 1932) cannot be applied successfully to the Lake Superior rocks.

(a) It is possible, by heavy mineral studies, to map certain areas characterized by minerals, or ratios of minerals, different from those of other areas of a batholith, even where the field and hand specimen studies show no petrographic differences. This may lead to suggestions of a composite origin where it was not otherwise suspected. And, of course, where field evidence suggests a composite mass, the study of heavy minerals may give strong confirmation.

(2). In a differentiated magma the accessory minerals are not necessarily the same in all facies. The hornblende granite of the Giants range is differentiated in a series with a variety of percentages of hornblende, and some samples show accessory sphene with no apatite; others, apatite with no sphene (Fig. 8a). The Keweenawan acidic differentiates in both Minnesota and Wisconsin had fluorite in several specimens but no fluorite in the basic differentiates. On the other hand, it is not safe to say that every differentiated mass will show different kinds of accessory minerals in different parts, for careful tests have been made on very few masses.

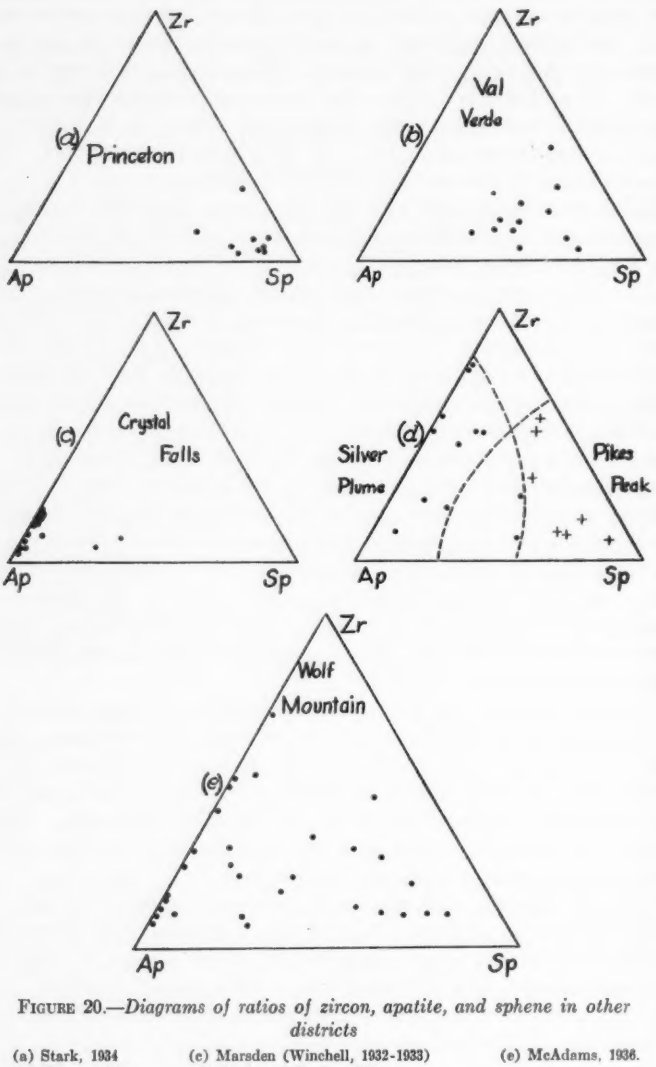

FIGURE 20.—*Diagrams of ratios of zircon, apatite, and sphene in other districts*

(a) Stark, 1934
(b) Wilson, 1937
(c) Marsden (Winchell, 1932-1933)
(d) Stark and Barnes, 1935
(e) McAdams, 1936.

(3). The ratios of accessory minerals may be very closely related to the differentiation process and products. This is well shown by the study of the Keweenawan rocks of Wisconsin, where the close association of the igneous rocks in one area and the similarity in age indicate a common magmatic source. Zircon, ilmenite, fluorite, sphene, and apatite show a striking change in relative percentage with a change in rock type. Zircon is common in acidic igneous rocks of the region but is rare in the basic rocks. In most samples of gabbro, trap, or anorthosite, zircon is either absent or so rare that it is not obtained even from a 200-gram sample. The relative percentage of zircon appears to be gradational, for rocks of intermediate composition contain a percentage of zircon intermediate between the percentages in granite and in basic rocks. Fluorite is in the acidic rocks but not in the basic rocks. Ilmenite occurs in all the rocks examined and varies in relative abundance even within a single rock type, as for example in the granite where it ranges from 10 to 64 per cent of the accessory minerals. Table 17 shows in general a larger amount of ilmenite in the more basic rocks. The relation between the relative percentage of apatite and the rock type is not clear because of the high percentage of ilmenite in the basic rocks. A marked increase in apatite relative to zircon is shown by the apatite-zircon ratio, as the rock becomes more basic. Certain differences may be seen in the data on Keweenawan igneous rocks from Minnesota (Table 11), but these are less clearly related to a series of differentiates. The work of Tolman (1936, p. 11-50) on the granites of Missouri also indicates a close relationship between the relative percentages of the accessory minerals and rock type.

Since the average relative percentages of the accessory minerals vary with rock type, any correlation of igneous rocks based on this feature is merely a correlation of similar rock types, and not a correlation of igneous rocks that are genetically related or of similar age. It should be noted also that the figures in Table 17 are averages of data that range rather widely. The relative percentages of heavy minerals in the granites of different ages (Tables 2, 3, 5) may show similar ranges so that no distinction can be made by the use of relative percentages.

Two megascopically like granites may have similar accessory mineral suites as an average of the whole mass, and individual samples in either mass may contain similar accessory mineral suites. On the other hand, two granites megascopically similar may have accessory minerals, such as zircon, that show notable differences in varietal characteristics.

(4). By noting certain features of zircons, correlation of granite outcrops has proved fully as valuable in Wisconsin and Michigan as Mackie found it in Scotland, but certain features need to be selected for close observation.

The variety of zircons in one granite is really rather great. A single sample may have zircons that are stubby and needlelike, euhedral and imperfect, simple crystal forms and complex modified forms, brown, colorless, and purple, zoned and uniform, rough and smooth (Pl. 2, fig. 1). A second sample of the same mass may lack one or two of these varieties, as for example, the zoning and the needle-like forms. A third sample may lack other varieties such as the truncation of simple forms by those of the second order, and the colorless grains. This gives a first impression that the zircons of a mass are so lacking in uniformity that no distinction or correlation can be based on them. Nevertheless, certain features are so nearly constant that they may be used. It is a dominance of a few features that characterizes the zircons of certain formations of certain ages, rather than a constancy in all features. The features most useful are those described in the data from Wisconsin in distinguishing the hyacinth, malacon, and "normal" types. There are probably many such masses elsewhere, as there are in the Lake Superior region. They are as much to be expected as masses with peculiar varieties of the abundant minerals in all parts of the mass. A recent paper refers to an igneous complex in which biotite had peculiar varietal characters in the whole mass (Deer, 1936). In support of this finding, note that Von Eckermann (1936) reports that the ratios of rare earth minerals, determined by quartz and X-ray spectrography, are remarkably constant through a differentiated series in Sweden.

The use of such characters as a limited range of forms and colors of zircon has been questioned by Nivers (1902), by Robertson (1923), by Watson and Hess (1913), by Chudoba (1937), and by Brammall and associates (1936). Several other men, knowing of the method, failed to find it a safe basis for correlation (Reed and Gilluly, 1932; Wells, 1931; Bruce and Jewett, 1936). It has nevertheless proved highly suggestive in this research in the Lake Superior region and may be extremely valuable.

(5). Even more important, there is in several districts a relation between distinguishable types of zircon and the geologic ages of the granite masses (Pl. 2). The hyacinth variety of zircon, for example, can be found in nearly every sample of known early pre-Huronian granite in Michigan and Wisconsin, and nearly every known pre-Animikie granite in Minnesota. On the south side of Lake Superior some late pre-Huronian granites and some Huronian granites show a dominance of malacon over other zircons, and Keweenawan rocks all around the west end of the lake show a dominance of simple forms, the "normal" zircon. One sample, or a few samples in a large series, may fail to show the zircon variety that appears in most of the samples from a batholith, but this can commonly be attributed to the use of too small a sample.

It is recognized, of course, that a granite batholith may rise in an area occupied by an older granite (Moore, 1931) and if it does it may include masses of older granite, or xenocrysts, with zircons which are of a type that is abundant in the older mass. Forms and associations suggesting such contamination have been noted in the Lake Superior region but are not common. The purple zircons with outer zones of malacon suggest xenocrysts of older rocks.

The value of the method may be emphasized by noting that two granites that differ megascopically like the hornblende granite and biotite granite of the Algoman Giants range have similar hyacinth zircons, whereas two granites megascopically as similar as the Keweenawan and earlier granites south of Penokee Gap have different types of zircon.

(6). The accessory minerals of two comagmatic igneous masses, with different cooling histories, may contain similar accessory minerals. This is shown by the study of a rhyolite flow and a comagmatic granite exposed in proximity near Mellen, Wisconsin. The zircons in an acidic flow from the gorge below Copper and Tyler falls in sec. 17, T. 45 N., R. 2 W., and granite from the SW¼ of sec. 31, T. 45 N., R. 2 W., were compared. Both rocks contain "normal" zircons in association with apatite and ilmenite. The zircons in the granite have the same crystal form, size, color, zoning, and inclusions as those in the rhyolite flow. The relative percentages of accessory minerals in the heavy separate from the flow are ilmenite 89, zircon 9, and apatite 1; and those from the granite are ilmenite 74, zircon 19, and apatite 5. Thus the relative percentages of accessory minerals in these two rocks are similar. If the ferromagnesian minerals are included with the accessory minerals, the relative percentage of the heavy minerals differ, for the flow contains only a trace of hornblende, whereas the granite contains about 1.6 per cent by weight of the ferromagnesian minerals, hornblende, chlorite, biotite, and epidote, and these make up 77 per cent of the heavy minerals.

The similarity of the zircon in these rocks formed under different conditions of intrusion and crystallization shows that the characteristics of accessory minerals may not be materially changed by considerable differences in the cooling history of the rock. If the cooling history has an important effect on the nature of the crystal form of zircon one would expect the crystals in the two rocks to differ widely. Probably some factor, such as a minor chemical constituent, largely controls the crystal habit. If so, it is reasonable to expect related igneous bodies to contain minerals having the same crystal habit. The effect of the addition of a small amount of impurity on the crystallization of a number of salts has been tested experimentally by Buckley (1930a, p. 443-466; 1930b, p. 15-31; 1931, p. 147-168), by Walcott (1926, p. 221-239, 259-277), and by

others. Their results show a change in the habits of crystallized salts when various impurities are added to the solution. Buckley (1931, p. 147-153) found that the physical conditions such as the rate of crystallization also have some effect on the crystal habit.

It is, of course, possible that the zircon in the rhyolite crystallized before extrusion. If so it may have formed under temperatures and pressures similar to those under which the zircon in the granite crystallized, and the physical conditions may have largely controlled the crystal habit. While this would explain the occurrence of zircon of like crystal habit in rocks having different intrusive and crystallization histories, experimental work makes it more probable that the crystal habit is directly related to chemical composition.

The occurrence of zircon having the same varietal characters in bodies having these different histories raises a question as to the validity of the theoretical conclusions reached by Wells (1932, p. 262). He believes it is a fundamental weakness in heavy mineral correlation that the intrusives, in order to have closely similar accessory minerals, must have had similar cooling histories. He states:

> "Only insofar as the cooling history of an intrusive has been unique can one reasonably expect the rocks to yield a distinctive heavy mineral suite; only inasmuch as the cooling history of two or more intrusions has been alike can one expect similarity in heavy mineral content. To use heavy minerals for correlation is to claim both the uniqueness of the first, and similarity of the second supposition."

Tolman and Koch (1936, p. 11-50) also hold this view. The facts about rhyolite and granite presented above show that a very different cooling history does not necessarily result in differences in the accessory minerals great enough to interfere with correlation. The theoretical discussion may omit some factor which has more definite control than the differences in cooling of a flow and a plutonic intrusive.

Even the study of Keweenawan rocks, however, includes one example in which varietal characters are affected by conditions of cooling. The variety of zircon in the granophyr differs notably from that of the granite, probably because of magmatic corrosion.

Thus, one example supports the theoretical conclusions of Wells, and the other does not. In fact the cooling conditions for rhyolite and granite are so very different that there is a strong suggestion that they have very little influence on a mineral like zircon.

(7). The varietal characteristics of zircon in early and late rocks of Keweenawan igneous period are much alike. It may be reasoned on a purely theoretical basis that the varietal characteristics of the accessory minerals in the various rocks of a prolonged period of igneous activity would change. The zircons in the detrital-inclusion suite of the Lower

Keweenawan sandstone, derived from early Keweenawan flows (since such zircons have not been found in pre-Keweenawan rocks), and those from the Keweenawan granite near Mellen, late in the igneous period, have the same crystal habit, color, and optical properties as those from the other Keweenawan rock types. In this test case the varietal characteristics of the zircon did not change through the entire igneous period.

(8). Varietal characteristics of zircon in various differentiation facies of a magma are much alike. A large gabbro mass has been intruded into the Middle Keweenawan series near Mellen, Wisconsin, extending from sec. 3, T. 44 N., R. 6 W., to sec. 7, T. 46 N., R. 1 E., a distance of about 40 miles with a maximum width of 6 miles (Fig. 4). It has differentiated into an anorthosite, a granophyr, and a gabbro facies. The zircons of these rocks show a greater variety in characteristics in the granophyr, than difference between that and the other facies. The unusual appearance of zircon in granophyr may be related in some way to the physical conditions of crystallization but probably not to the differentiation history. Grains and crystals showing a similar habit occur in both the other facies.

The granite near Mellen and the Keweenawan flows are closely associated in their areal distribution with the gabbro intrusive and appear to be related genetically, since these rocks are all a part of one period of igneous activity. The zircons in the granite, rhyolite flow, and the various facies of the gabbro are very similar, showing that the differentiation history of a rock need not alter the character of the zircon.

(9). The kinds and ratios of detrital heavy accessory minerals of sediments, which have proved serviceable for correlation of beds in the Paleozoic and later rocks, serve well in the Keweenawan.

(10). The kinds and ratios of heavy minerals in sediments older than Keweenawan are less valuable, but some correlations may be made by the use of the varietal characters of zircons, and all the older rocks can be sharply distinguished from the Keweenawan.

In Huronian and older sediments metamorphism is a complicating factor. It is difficult to distinguish the detrital from the authigenic minerals and those produced in metamorphism. No data are available to show whether or not metamorphism of a certain grade may attack the accessory minerals so far as to change their peculiar varietal characters.

Since three intrusive periods in the Lake Superior region have distinguishable varieties of zircon assemblages, it follows that the zircons in the sediments should give valuable clues as to the age of the sediments. For example, if a sediment in this region has zircons of hyacinth and malacon types, it is younger than the intrusives that contain mala-

cons—those of the second oldest igneous period in the district, distinguishable by varieties of zircon. It cannot be said how much younger, unless other information is added. No mineralogic data found so far will indicate whether the peculiar zircons came from one particular intrusion or from a certain direction. Warning should be added that other minerals cannot be expected to serve as well as zircon in tracing sediments to their source. Possibly some may serve, at least locally.

(11). Changes in accessory minerals during sedimentation. Boswell in 1916 cited half a dozen cases in which the accessories by their distribution, associations, or peculiarities indicated the source of certain sediments. Since then the papers making reference to such source determinations have increased to perhaps 20 or 30. The principles underlying such work were discussed by Boswell (1916) and by Mackie (1925). A large part of the subject is concerned with changes in accessory minerals during sedimentation. This is a subject about which there are numerous suggestions but relatively few data. Three or four districts in the Lake Superior region add significant points. Plate 1 shows the distribution of the Pokegama quartzite along the south slope of the Giants range with the width of quartzite only slightly exaggerated. Where the quartzite is not mapped, the iron-bearing rocks overlap across the quartzite. The quartzite actually thins out, however, near the east end. The basement complex, which may have contributed to the quartzite, is shown by a pattern rather than by a label on the map area. The abundance of granite pebbles in the basal conglomerate, lying on granite of the same character, is proof that the sediments received large contributions from the granite, although some material from distant sources was probably added. The importance of such contributions is not easily determined by field exposures.

Figure 8 shows the changes in certain ratios. Others might be selected from Tables 7 and 9.

The Saganaga granite contributed boulders to the conglomerate west of it, and this grades up into the sandstones and slates sampled in this study. The changes in the ratios of apatite, zircon, and sphene from the source to the sediment are shown in Figure 12, which corresponds fairly well with results shown in Figure 8 for the Giants range.

The Keweenawan sediments of Minnesota furnish somewhat less satisfactory data (Table 15). The shaly sands derived from flows and tuffs of basalt and rhyolite are so rich in magnetite that the other accessory minerals are wholly subordinate. Zircon and sphene are found in so few samples that their ratios are not significant. Aside from the opaque oxides, apatite is the chief accessory mineral, and Figure 13 shows the ratios of iron oxides (plus leucoxene) to apatite, in a group of three sedi-

ments, according to the closeness of their relation to the igneous rocks: (1) those interbedded with flows, (2) those near the outcrops of flows, and (3) the Hinckley sandstone in Pine County. The Hinckley seems to be conformable with the sediments near the flows and its low apatite

TABLE 14.—*Changes in heavy minerals*
Probably resulting from sedimentation, along the Giants range

	In granite	In quartzite
Actinolite (s)	none	rare
Allanite	rare	none
Anatase (s)	very rare	common (s)
Apatite	very common, small	common, large
Augite	rare, green	none
Biotite	very common	rare
Carbonates (s)	rare	rare
Chalcopyrite (a)	very rare	none
Chlorite (s)	very common	rare
Collophanite (a)	none	rare
Diopside	none	very rare
Epidote	common (s)	common
Fluorite	rare, purple	none
Galena (a)	rare	rare
Garnet	local, pink crystals	common, rounded
Hematite (s)	rare	common
Hornblende	very common, green	common
Ilmenite	common	rare, -altered
Leucoxene	common (s)	common
Limonite (s)	rare	common
Magnetite	very common	very common
Monazite	none	very rare
Muscovite	common	rare (s)
Pyrite (a)	common	common
Pyrrhotite (a)	local	none
Rutile	rare (s)	rare
Sphene	very common, irregular	rare
Tourmaline	rare	very common, large
Tremolite (s)	none	rare
Zircon	very common	very common
Zoisite	common (s)	rare

(s)—secondary.
(a)—added by introduction.

content suggests that that mineral is more rapidly attacked than opaque iron ores.

The Oronto sediments have an abundance of angular to subangular grains and pebbles of acidic and basic extrusive rocks showing very clearly that the group was derived largely from the Keweenawan flows. The pebbles of quartzite, slate, iron formation, and granite indicate that the older rocks of the region also were supplying material to the area of Keweenawan sedimentation.

The detrital and detrital-inclusion heavy minerals show with equal clearness that the main provenance of the Oronto sediments was the Keweenawan extrusive material. The epidote and ilmenite so abundant in these sediments were probably derived from the basic flows. The

TABLE 15.—*Changes in heavy minerals*

Probably resulting from re-working of Keweenawan flows to Red Clastic sediments in Minnesota

	In flows	In sediments
Anatase	very rare	rare
Apatite	rare	very common
Augite and olivine	very common	none
Biotite	common	very rare
Carbonates	common	dissolved in laboratory procedure
Chlorite	common	
Epidote	common	very rare
Fluorite	rare	rare
Garnet	very rare	common
Hornblende	rare	very rare
Ilmenite and leucoxene	common	common
Magnetite and hematite	common	common
Pyrite	common	none
Rutile	very rare	very rare
Sericite	rare	none
Sphene	rare	none
Tourmaline	very rare	common
Zircon	rare	common

detrital zircons are dominantly clear to slightly yellowish subangular to rounded grains strongly suggesting a Keweenawan source. The abundance of perfect crystals of "normal" zircon in the detrital-inclusion suite of the Oronto sediments indicates rather definitely that the Keweenawan igneous rocks were the major source. Thus the heavy mineral evidence agrees with and supports the field evidence of the origin of the Oronto sediments.

Malacon and hyacinth occur in minor quantities in the Oronto sediments. The hyacinth may have been derived from the Huronian sediments or the pre-Huronian rocks. That the Huronian certainly supplied some material is indicated by the presence of quartzite, slate, and iron formation pebbles. Two boulders of granite from the Outer conglomerate near the Montreal River contain malacon, indicating clearly that a granite containing malacon was unroofed by Oronto time.

The Oronto sediments are characterized by a rather small but constant percentage of garnet which has not been reported from any of the Keweenawan igneous rocks of the region. The garnet and the sporadic staurolite were probably derived from previously metamorphosed Huron-

ian sediments. There seems to be little doubt that the Oronto sediments were derived dominantly from the basic and acidic Keweenawan extrusive rocks and that they have probably not been transported far.

Table 16 gives the general mineralogical composition of the Keweenawan igneous rocks as compared with the Oronto sediments. The most important mineral changes which have taken place during the weathering, transportation, and deposition of the detritus are the complete loss of olivine and pyroxene and the general elimination of chlorite, biotite, hornblende, and sphene. Anatase and leucoxene appear in the sediments as alteration products of ilmenite and sphene, whereas garnet and staurolite have probably been derived from some source other than the Keweenawan igneous rocks of the Wisconsin-Michigan area. These factors indicate clearly that the Keweenawan igneous rocks underwent sufficient weathering to eliminate most of the ferromagnesian constituents before final deposition of the sediments.

Evidently during sedimentation, sphene disappears or becomes so altered as to be unrecognizable. Possibly a warning should be added because sphene has been found in some rocks by a special treatment, though not recognized without that treatment (Mackie, 1919). The data on the granite masses suggest that epidote is attacked much more than apatite or zircon, but the data for basic rocks do not wholly agree. The investigated samples are too few to be more than suggestive; more studies of the sort are needed. As between apatite and zircon, the tendency of sedimentation in these four districts was clearly to remove apatite faster than zircon, but not so fast as sphene.

Many papers refer briefly to similar changes that occur in accessory minerals during sedimentation. Mackie (1925, p. 138, 146) notes that changes may result from (1) mechanical concentration, (2) selective solution, and (3) intrastratal changes. The fluorite and apatite are mentioned as especially soluble, hornblende somewhat so, iron ores and sphene less soluble, and tourmaline persistent. Simpson and Stuart (1934) report that pyrrhotite cannot survive as a detrital for any appreciable time. It is reported in several places that hornblende and augite disappear before traveling far from their sources (Becker, 1931; Shannon, 1927). The Whin sill contributes some rock fragments to sediments near-by, but the minerals are lost before they are broken from the pebbles as mineral grains (Hawkes and Smythe, 1931). Boswell claims that staurolite and garnet are so resistant that they may survive several cycles of sedimentation (Boswell, 1917). Leith and Mead (1915) give a list of the resistant accessories, naming monazite, zircon, sphene, and garnet.

Caution should be observed in all such studies because it is reported (Edelman and Doeglas, 1931) that even some of the more persistent minerals can be etched and are therefore soluble—staurolite, garnet, epidote, sphene, and disthene, as well as hornblende and augite.

TABLE 16.—*Comparison of mineralogical composition*

Of middle Keweenawan igneous rocks with the upper Keweenawan Oronto sediments.

Minerals	Igneous rocks	Oronto sediments
Apatite	rare	common
Biotite	common	very rare
Chlorite	common	very rare
Epidote	common	common
Feldspar	very common	abundant
Fluorite	rare	none
Hornblende	rare	very rare
Ilmenite	common	common
Leucoxene	common	common
Magnetite	common	rare
Olivine	very common	none
Pyroxene	very common	none
Quartz	common	abundant
Rutile	very rare	rare
Sphene	rare	very rare
Staurolite	none	rare
Tourmaline	very rare	common
Zircon	rare	common
Zoisite	common	common

Other studies refer to such effects on minerals in general terms and more or less incidentally to other matters (Clarke, 1924; Leach, 1928; Mackie, 1925-1926). It is clear that pyrite and apatite are quickly removed, especially if carbonic acid attacks the apatite. Zircon, corundum, and others are not absolutely incorrodible but nearly so.

Some of the changes from igneous rock to weathered or sedimentary derivatives are very surprising. It is reported that quartz is the most important mineral in the fine sands of soils derived from basalts (Nichols, 1936). The proportion of garnet in the heavy accessory minerals of weathered amphibolite may be over seven times as great as that in the original rock (Goldich, 1938).

This summary of effects in actual transportation and deposition may be compared with the series by Freise (1931) "bei Verfrachtung im Wasser," and by Cozzens (1931) on rates of wear. Freise's scale of resistance with higher numbers for the more resistant includes: garnet, 420; epidote, 320; apatite, 275; zircon, 265; monazite, 120. Tests now

in progress at Minnesota indicate that apatite is more rapidly attacked than zircon, and probably several other changes are to be made in the scale. The minerals tested to date, in order of increasing resistance are: apatite, hornblende, microcline, garnet, tourmaline, and quartz (Thiel, in press).

TABLE 17.—*Variations in the average relative percentage of minerals in the total heavy accessory minerals*

In the Keweenawan igneous rocks in Wisconsin

Rock type	Zircon	Apatite	Fluorite	Sphene	Ilmenite	Leucoxene	Apatite-zircon ratio
Granite	26	11	5	17	41	.....	30–70
Granophyr	18	6	.....	1	60	15	25–75
Rhyolite	9	2	x	.....	89	x	18–82
Granodiorite	10	24	.....	1	64	.....	70–30
Anorthosite	x	x	.....	x	99	.....	x– x
Gabbro	x	1	.....	1	97	.....	1– x

x=less than 1 per cent.

It is also to be noted that sphene is not listed or given a number in Freise's table. It probably disappears more promptly than epidote. Cozzen's table shows that sphene wears faster than orthoclase and quartz, but there are no data on other common granitic accessory minerals.

With these in mind, it is not surprising that the Pokegama quartzite has regularly much tourmaline, whereas the granite has tourmaline in a very small proportion of samples. Contributions from distant sources might be thought of at once but are very uncertain.

Evidently students should not be too ready to assume a foreign source for sediments resting on crystalline basements, even if the heavy accessory minerals seem to be notably different (Winchell, 1933, Appendix F, p. 2, 3).

A further conclusion is that it is useful to study other heavy minerals besides the accessory minerals in igneous rocks. The tables show that some of the abundant minerals persist better than others and appear as accessory minerals in the sediments. Until we know the relative resistance of minerals better, we may lose many significant features in the study of sources of sediments unless all the heavy minerals of the source rocks are noted. Figure 8b shows how epidote changed its ratios to apatite and zircon during sedimentation. Such changes cannot be detected in heavy mineral studies unless some attempt is made to record at least approximate figures for the more abundant minerals.

NEED FOR FURTHER WORK

All the workers co-operating in this research found numerous unsettled questions. Several, especially relating to the technique, have been settled during the work, but more remain to be settled later. This final section suggests what are believed to be the subjects most in need of study before the methods are given approval as valuable for studies in new districts.

(1). The methods of handling rocks should be more strictly standardized. The problem was considered in the report by the committee of the National Research Council, May 1, 1937.

(2). Several more large igneous masses should be studied by test of about 100 scattered samples before it is safe to say that masses show any constancy in ratios of heavy accessories. It may be expected that a few will show a limited range or approximate constancy of ratios, but the data now at hand suggest that constancy will not be found in very many.

(3). The work on different varieties of zircon should be extended, and varietal differences should be sought in other resistant minerals. The differences found in zircon varieties in Wisconsin and Minnesota should be carried in all directions to neighboring districts to see if the methods are reliable and generally applicable in pre-Cambrian problems.

(4). More districts should have tests of the accessories of a group of formations such that the older rocks seem to have contributed the material for the overlying sediments. It is not yet possible to predict with any confidence which accessories are lost most rapidly and which are most persistent in the process of sedimentation and after deposition as sediment. Experimental work in abrasion and attack of water on minerals will be useful.

Closely related to this are studies of the changes in heavy accessories in rocks weathered in place. Many more such studies are needed for comparison with the studies of persistence during sedimentation.

CONCLUSIONS

(1). To make the heavy accessory mineral work of one group comparable with that of another requires either that the methods be standardized in great detail, or that the methods used by each group be checked by the methods of the other.

(2). Few igneous masses are likely to show any constancy in total or relative amounts of heavy accessory minerals.

(3). The relative amounts or ratios of one mineral to another differ with igneous rock type, in a general way.

(4). Certain igneous masses have heavy mineral assemblages in which the dominant zircons are of one variety which can be clearly defined and distinguished from others.

(5). Insofar as the rocks of the Lake Superior region have been tested, a certain variety of zircon may dominate the zircons in the heavy minerals of all masses of a certain age.

(6). Three such varieties have been distinguished in Wisconsin, under the terms hyacinth dominant in the early pre-Huronian (and pre-Animikie in Minnesota), malacon dominant in the Huronian and late pre-Huronian, and "normal" (or Keweenawan type) zircon dominant in the Keweenawan igneous rocks.

(7). Differentiation, depth, and rate of cooling in a series of Keweenawan igneous rocks had only a very minor influence on such varietal characters as are here distinguished, and the characters persist through the whole period from early to late Keweenawan.

(8). Ratios and kinds of heavy accessory minerals serve to correlate certain Keweenawan sedimentary beds around Lake Superior but are not satisfactory in older beds because of the metamorphism of the authigenic minerals and of the minerals included in the clastic grains. The older rocks, however, are clearly distinguished from the Keweenawan.

(9). Some information as to age of pre-Keweenawan rocks can be gained from the varieties of zircon contained, since they are derived from igneous rocks distinguished as in (6).

(10). The changes in heavy accessory minerals during weathering and sedimentation have been noted in four districts and since they are not quite like those of published earlier reports they suggest the need of further work.

(11). These conclusions have been applied to rocks in Wisconsin; Michigan and Minnesota have brought forth suggestions of probable correlations of importance. All intrusives, whose ages are clearly shown by field evidences seen, have zircon varieties suggesting the same age as the field evidence. The sediments of the upper Keweenawan have accessory minerals suggesting a new simplified sequence, which agrees well with the field evidence.

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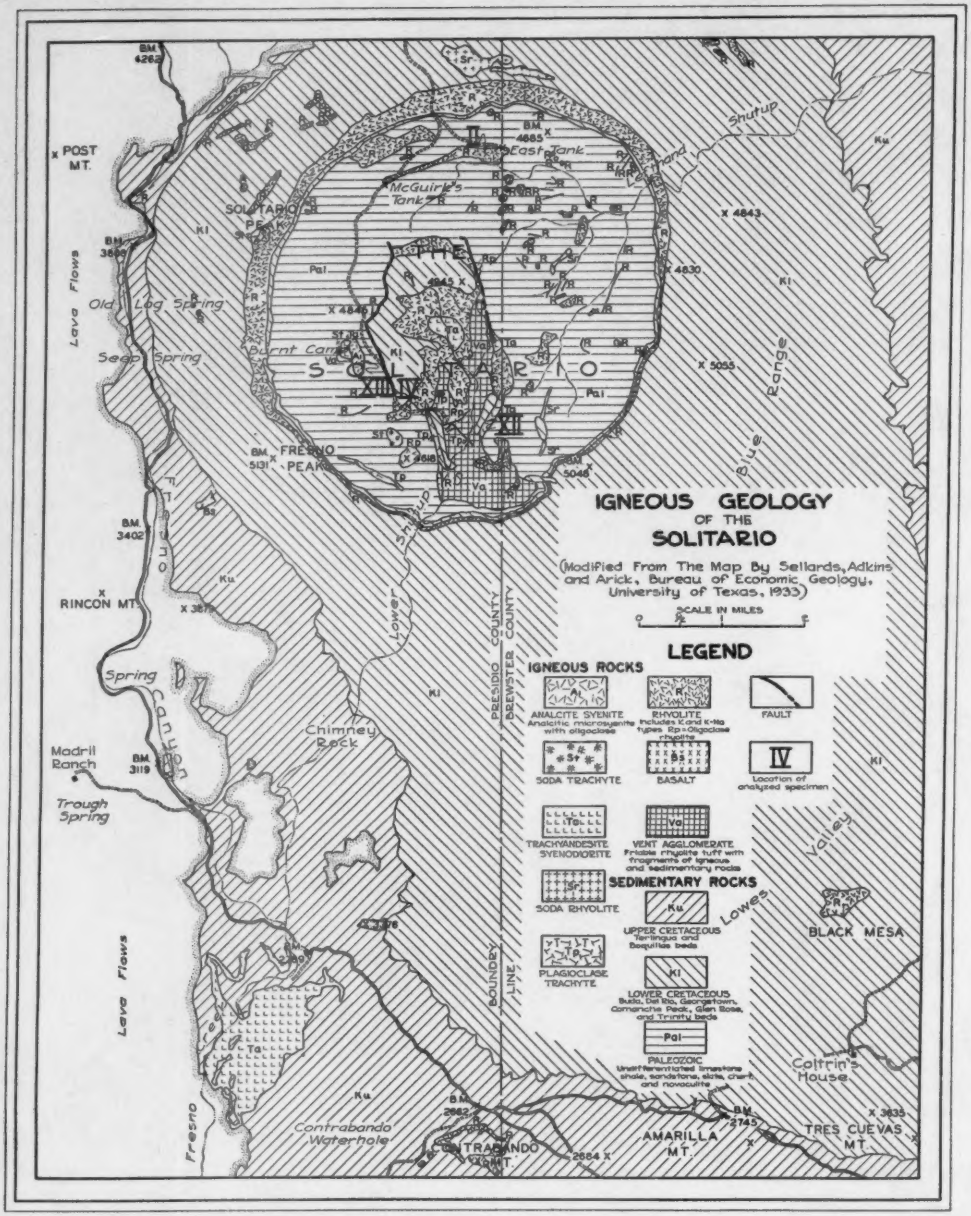

IGNEOUS GEOLOGY OF THE SOLITARIO

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IGNEOUS ROCKS OF THE TERLINGUA-SOLITARIO REGION, TEXAS

BY JOHN T. LONSDALE

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ABSTRACT

The Terlingua-Solitario region in southern Brewster and Presidio counties, Texas, is arid and mountainous with many hypabyssal intrusions. Lava flows border it on the west. The sedimentary rocks, excepting some of Paleozoic age in the center of

the Solitario, the largest laccolithic dome, are Cretaceous and have been deformed by laccolithic intrusions and faults, many of the rift type. The Solitario contains many small rhyolite dikes and sills and is encircled by a rim sill. Volcanic agglomerate in a central cauldronlike area records an extrusion. The eastern part of the area is in a block depressed several thousand feet and contains many dikes, sills, and smaller laccoliths.

The igneous rocks include an analcite-bearing series and intermediate, trachytic, and rhyolitic types, most of which are soda-rich. The analcite-bearing types range from melanocratic gabbroid to syenitic types. Analcite is primary, deuteric, and hydrothermal and was formed through a rather long period. The complete assemblage is alkaline and resembles the suites from Spanish Peaks, Colorado, and other alkaline subprovinces along the front of the Rocky Mountains.

The analcite-bearing rocks are most abundant in the sunken block and evidently were derived from several differentiating submagmas. The other rocks, especially the rhyolites, are associated with higher anticlinal structures. A tectonic control of differentiation is postulated.

INTRODUCTION

The Terlingua-Solitario region in the Big Bend country of Texas is well known for its striking geologic structures, arid mountain scenery, and production of quicksilver. Hill (1902), Udden (1907; 1918), Turner (1906), Powers (1921), Baker (1935), and Sellards and associates (1932; 1933) have described the remarkable Solitario uplift, the complex structure and stratigraphy, and the deposits of quicksilver. Though igneous rocks have long been known in the region, they have received very little attention. It has been recognized that some of the rocks are alkaline and that the complete assemblage might be of interest. It is now known that the rocks include many analcite-bearing members along with other alkaline types. Two series are present. Rhyolite, trachyandesite, and related types predominate in the Solitario, and possibly extensive lava flows to the west are related to this series. The other series is common in the country east of the Solitario and includes the analcite-bearing rocks. Over 300 separate mappable igneous masses are present in the area, most of which are shown on the maps (Pls. 1, 2).

FIELD WORK AND ACKNOWLEDGMENTS

The months of June and July 1928 were spent in the field with W. S. Adkins and M. B. Arick under the auspices of the Bureau of Economic Geology, University of Texas, making a comprehensive geologic survey of the region. Data secured from this work have been made available through the kindness of Dr. E. H. Sellards. June, July, and August 1937 were spent in additional field work made possible by a generous grant from the Penrose Bequest of The Geological Society of America. This grant also defrayed the cost of thin sections and of 20 chemical analyses made by Dr. R. B. Ellestad at the University of Minnesota.

C. L. Baker spent several days in the field with the writer and has generously helped in many ways during the course of the work. Adolph

Knopf loaned sections of Spanish Peaks rocks and very kindly identified alkali feldspars in four rocks. He also gave valuable advice concerning classification of the rocks. C. P. Ross of the United States Geological Survey loaned sections of some of the rocks collected in connection with

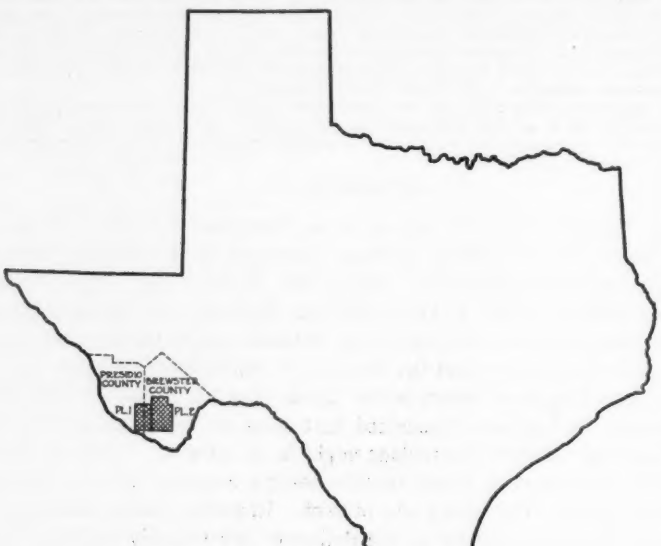


FIGURE 1.—*Index map*

his study of the quicksilver deposits. H. P. Stocking who assisted Ross made available his petrographic descriptions of the nonanalcitic rocks.

LOCATION OF THE REGION

The Terlingua-Solitario region as here designated comprises about 400 square miles in the southern part of the Big Bend country of Texas, about 225 miles southeast of El Paso, and includes those parts of the Terlingua and Agua Fria quadrangles in which igneous rocks are abundant (Fig. 1). Terlingua is a mining camp, and the Solitario is in the northwestern part of the area. Alpine and Marathon, 86 miles north of Terlingua on the Southern Pacific railway, are the nearest towns. The recently designated Chisos Mountains Park adjoins the area on the south and east.

The area is a relatively small unit in a vast region in Texas where igneous rocks are common. The lava flows in the western part of the area are only the border of a very extensive field. In the Chisos Mountains to the east and in other mountain areas north and northeast, intrusive and extrusive rocks are abundant. However, the Terlingua-Solitario area probably is important in the petrology of the region because of the excellent exposures and diversified types of rocks.

GEOLOGIC AND PHYSIOGRAPHIC SETTING

The Terlingua-Solitario region is arid and mountainous. Its physiographic make-up exemplifies strikingly the erosion of rocks differing markedly in resistance to erosion and occurring under complex and diversified structural conditions. The region, generally, is a part of the great sunken block described by Udden (1907) and Baker (1935), bounded on the southwest by the great fault near the Grand Canyon of Santa Helena and on the northeast and east by the Sierra del Carmen, a broad step-faulted domical uplift. In this area, about 39 miles wide, the country has been dropped 4000 to 6000 feet. To the northwest the settling decreases and ends with the Solitario uplift, which is flanked on the west by a great lava field. The sunken block is extensively folded and faulted. The more important local uplifts include the Chisos Mountains and Christmas Mountains, in which the amount of uplift has been several thousand feet. Numerous smaller anticlinal structures range from domes only a few hundred feet in diameter to larger anticlines several miles long and including many laccoliths. Practically every part of the area has been deformed to some degree, and many blocks of sediments are tilted with dips up to 30 degrees. Many of the folds are nearly equidimensional, suggesting unexposed laccoliths. Most elongate folds trend northwest.

The Solitario uplift is a broad anticline surmounted by the Solitario proper, a circular dome about 9 miles in diameter. The anticline extends to Terlingua, where quicksilver deposits are found (Udden, 1918). The Solitario proper has been raised several thousand feet above the general structural level of the anticline. Erosion has developed a central circular basin about 5 miles in diameter enclosed in a rim of Cretaceous sediments which at the inner margin dip outward as much as 45 degrees. The central part of the basin contains highly folded and faulted Paleozoic sedimentary rocks and many younger igneous masses.

Faults are prominent. The major ones are related to the Solitario uplift and trend northwest; others trend at right angles to the first set. The bounding fault near the Grand Canyon of Santa Helena has a dis-

TABLE 1.—*Summary of Cretaceous formations in the Terlingua-Solitario region*

Age	Group and formation	Character	Thickness (Feet)	Remarks
Late Upper	Aguja	Coarse fossiliferous sandstone, dark, lignite-bearing shales, and massive silty clays	600	Least resistant to erosion. Exposed in structurally low areas of Long Draw, Sawmill Canyon, southwest of Hen Egg Mountain, and in synclines northeast of Terlingua.
Upper	Terlingua	Gray marl and clay with concretionary limestone	1250	More resistant to erosion than upper Cretaceous beds. Exposures flank the Solitario, Adobe Walls anticline, Packsaddle Mountain, and other high anticlines and form crests of lower structures. An extensive exposure found between Sawmill Mountain and Hen Egg Mountain.
	Boquillas	Flaggy limestone grading upward into thin beds of chalk and marl	600	
Lower	Buda	Whitish, dense, brittle limestone	50	Resistant to erosion. Exposed mainly in and around Solitario and in higher anticlinal structures such as Packsaddle Mountain, Mountain 4318. and Adobe Walls anticline. Glen Rose, Comanche Peak, and Trinity exposed only inside Solitario.
	Del Rio	Clays, clay shales, and thin-bedded limestone	60 to 100	
	Georgetown Edwards Comanche Peak Glen Rose	Mainly massive, heavy-bedded limestone, lower part containing interbeds of softer marls, shales, and sandstone	2000±	
	Trinity	Conglomerate and coarse sandstone	50±	

placement of 3000 feet. The Long Draw near Terlingua is a rift about 9 miles long and 2 miles wide with vertical displacement of 500 to 1000 feet on the north and 1500 to 2000 feet on the south. Other narrow dropped blocks are located along Saltgrass Draw and southwest of Hen Egg Mountain. East of Hen Egg Mountain the south flank of a prominent domical uplift is bounded by an east-west fault with displacement of about 1000 feet.

The region displays igneous rocks, massive and shaly limestones, shales, and clays. These vary greatly in their resistance to erosion. The highly resistant igneous rocks and massive limestones form mountains, mesas, and other higher topographic features. The limestones are low in the stratigraphic column and outcrop only in anticlines and along faults. Many of the intrusions ascended into the softer rocks, and erosion has left them in topographic prominence. Inasmuch as anticlines, faults, and intrusions are abundant and of various sizes, there has resulted a picturesque topography all the more striking because the very small amount of rainfall produces only limited scrubby vegetation.

Approaching the region from the north, one passes from a country of no great relief, and with only occasional isolated mesas and mountains, into one with numerous sharp peaks and ridges of igneous rocks, mesas and ridges of limestone, and lower, less rugged clay and shale areas. The country to the north has an average altitude of about 3300 feet. In the northern, northeastern, and eastern part of the Terlingua-Solitario region many igneous mountains rise above this general level to a maximum of 5000 feet at Hen Egg Mountain. The rim of the Solitario is generally higher than 5000 feet, and the lava flows to the west are well above 4000 feet. The central and southeastern parts of the region, in the lower part of the sunken block, are much lower, sloping from the mile-high rim of the Solitario to elevations of less than 2500 feet along Terlingua Creek east of Terlingua. The relief in this lower part of the area is still pronounced because of igneous and limestone mountains or mesas and the rift valleys and fault escarpments.

SEDIMENTARY ROCKS

The sedimentary rocks with the exception of those in the center of the Solitario are of Cretaceous age (Pls. 1, 2). The most important features of the Cretaceous rocks are shown in Table 1.

Paleozoic rocks are found only in the inner basin of the Solitario. They are intricately folded and faulted and partly metamorphosed extensions of the sediments of the Marathon basin (Sellards, 1932; Baker, 1935, p. 177). Cherty marbles, quartzites, sandstones, hard shales,

novaculite, chert, and limestones are present and they range from Pennsylvanian (?), Devonian (?), Ordovician, and Cambrian to possibly pre-Cambrian age.

IGNEOUS GEOLOGY

GENERAL STATEMENT

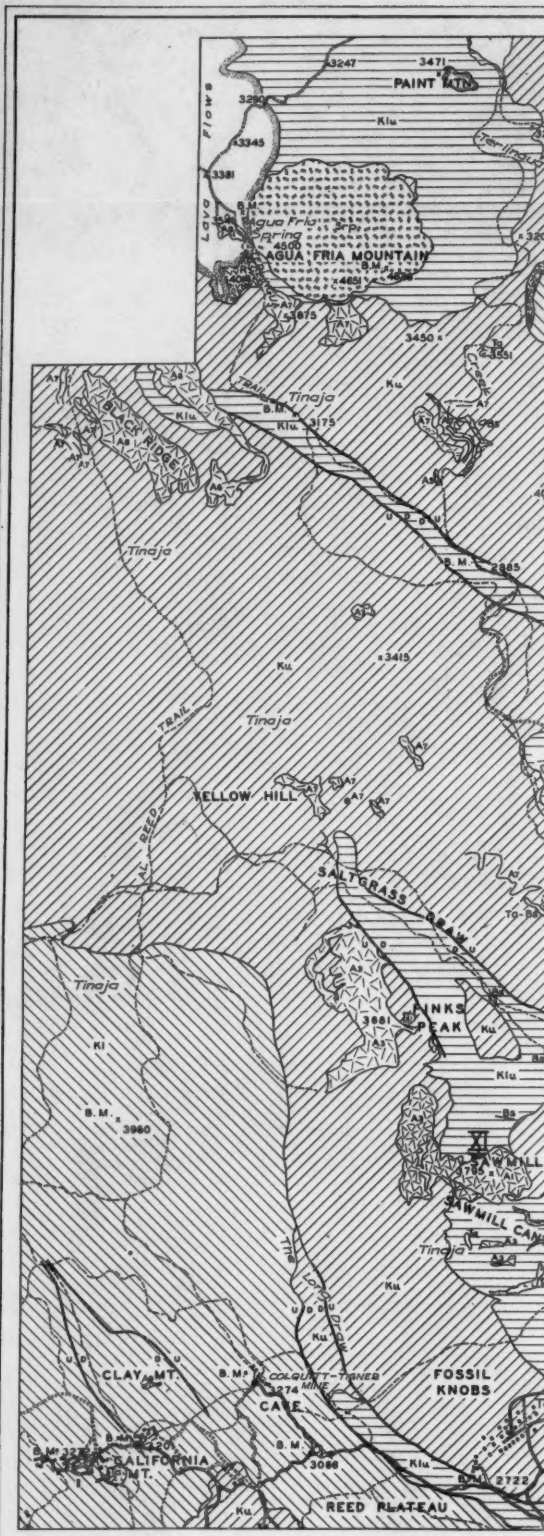
The igneous rocks consist of several hundred mappable masses which occur as lava flows, plugs or necks, dikes, sills, laccoliths, bysmaliths (?), and possibly stocks (Pls. 1, 2). Many are well exposed so that their relations to the sedimentary rocks are clear, but unfortunately there are not very many significant crossings of igneous rocks with each other. Laccoliths are the largest intrusions, and of these the Solitario is the most important.

THE SOLITARIO

General description.—The Solitario proper is a circular dome about 9 miles in diameter with structural relief of several thousand feet. The perfection of the structure has led most observers to conclude that its origin is igneous and that it probably spans a laccolithic mass. Many small intrusive bodies, generally sills and dikes, strengthen the conclusion. However, the Solitario is more than a buried laccolith with satellite dikes and sills because probably its history included an extrusive episode and the development of a cauldronlike depression. Powers (1921, p. 421, 426) recognized clearly that extrusive action was an essential part of Solitario history, but later investigators have not mentioned this fact.

Most of the exposed igneous rocks are in the central part of the structure within a continuous Rim sill which encircles the inner basin at the general horizon of the Trinity conglomerate. The few masses outside this Rim sill are sills and dikes. Within the basin and intruding the folded Paleozoic rocks are many small masses, mostly dikes and sills, but possibly some are plugs. Many of the smaller masses are nearly equidimensional in ground plan but have been controlled by the structure of the Paleozoic rocks.

The most significant masses of igneous rocks are in the central and south-central parts of the basin in a fault block which has been dropped at least 2000 feet (Pl. 1). This block, completely surrounded by Paleozoic rocks, contains Edwards and older Lower Cretaceous limestone, which, if the central part of the dome were intact, not eroded, and not faulted, would occupy a position far above the present surface. The igneous rocks, which cover about three-fourths of the area of the fault block, consist of a large mass of rhyolite, which has been intruded by dikes and irregular masses of syenodiorite porphyry, trachyandesite, and plagioclase trachyte, and a central mass of volcanic agglomerate or vent agglomerate which occupies lower areas and which likewise has been


PAINT
AGUA FRIA MOUNTAIN
Agua Fria Spring
Lava Flows
Tinaja
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BLACK RIDGE
YELLOW HILL
SALTGRASS DRAW
PINKS PEAK
SAWMILL CANYON
CLAY MT.
CALIFORNIA MT.
COLQUHOUN MINE
FOSSIL KNOBS
REED PLATEAU
TRAIL
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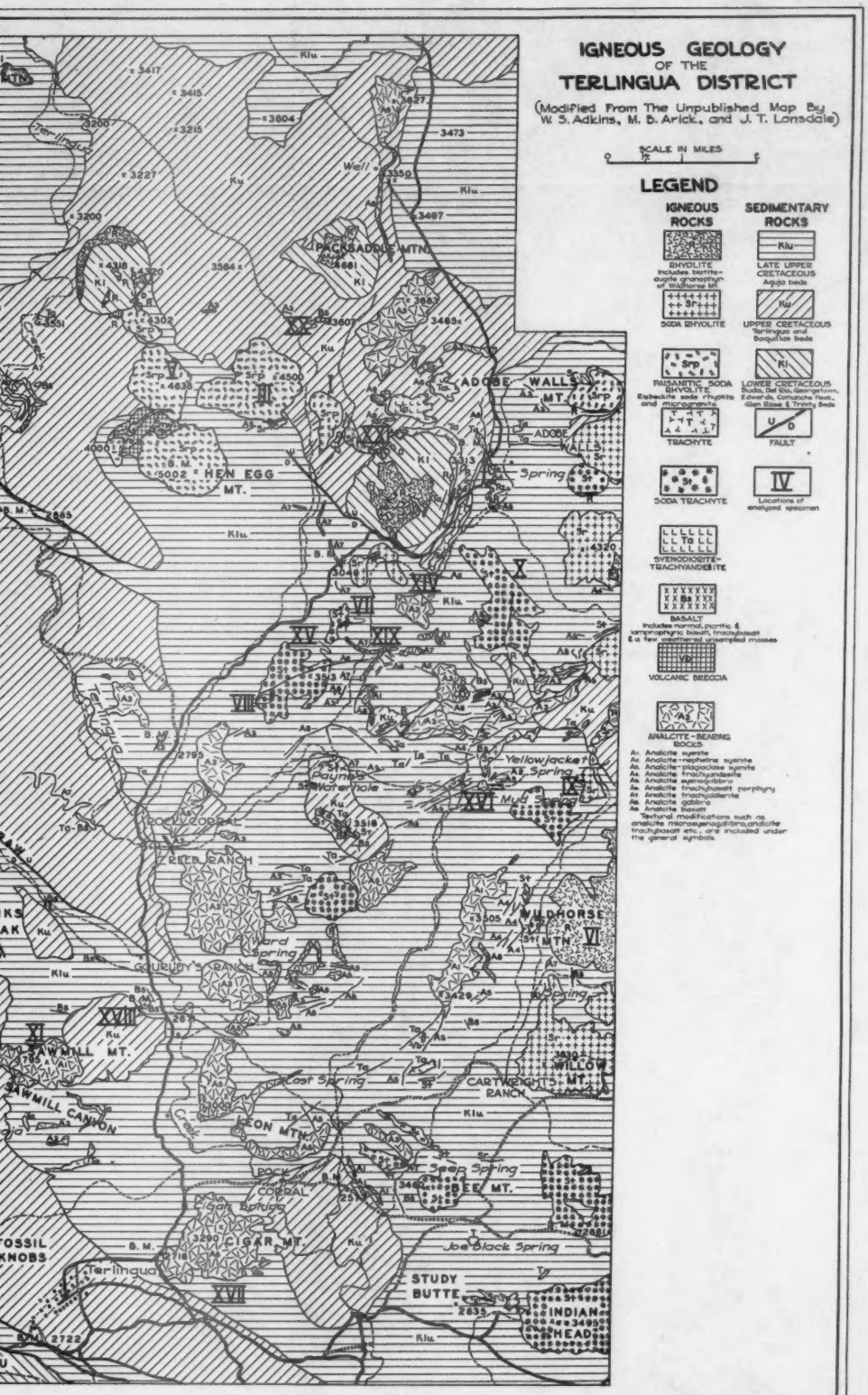

NEOUS GEOLOGY OF THE TERLINGUA DISTRICT

intruded by the syenodiorite porphyry and by dikes of rhyolite and trachyte.

The rhyolite forms a nearly continuous but very irregular outcrop. Its northern part is a narrow sill-like body between Paleozoic rocks and Cretaceous limestone or in some places at the level of the Trinity conglomerate. Here it could very well be a part of the Rim sill preserved by its present depressed position. Farther south the rock appears to be stratigraphically slightly higher. A smaller mass of similar rock occurs at the east side of the fault block. The faults bounding the block cut the rhyolite as well as the sedimentary rocks. At the east boundary, rhyolite occurs on the downthrown side of the fault, while a few hundred feet south syenodiorite porphyry is present on the upthrown side. Inasmuch as the rhyolite elsewhere is intruded by syenodiorite porphyry, intrusion of the syenodiorite probably followed the faulting, and the magma moved upward along the fractured zone at the margin of the dropped area, much as in cauldron subsidence.

Other features add to the suggestion that this occurrence involved subsidence somewhat like the cauldron type. Near the southern end of the block narrow masses of syenodiorite porphyry and plagioclase trachyte a few hundred feet wide and several hundred yards long are separated from the vent agglomerate by narrow bands of Cretaceous limestone. These igneous masses probably mark the position of the faults, and the limestones represent the outer part of the dropped block. The extreme southern part of the igneous area contains only vent agglomerate, and the boundary relations are not apparent.

Vent agglomerate.—The vent agglomerate has a white to bluish-gray felsitic matrix cementing fragments of igneous and Cretaceous and Paleozoic sedimentary rocks (Pl. 4). The fragments range from shot size to blocks of limestone as much as 20 feet in diameter. Where inclusions are scarce, outcrops of felsitic matrix are glaring white and incoherent. In stream beds where erosion has removed weathered material, the felsite is coherent. Where inclusions are abundant, the exposures are greenish to bluish gray.

The felsite is rhyolitic and in places porphyritic. Near the northern boundary of the outcrop the rock is lavender, ashy, with faint flow lines, and a few visible inclusions. It contains sporadic corroded quartz crystals as large as 0.8 by 0.6 millimeter and abundant soda sanidine crystals up to 2 by 0.5 millimeters in a microfelsitic groundmass. Minute zircons and shreds of biotite are rare. Near the center of the outcrop the matrix is a white to cream colored, ashy porphyry with a microfelsitic groundmass with phenocrysts of microperthite, altered oligo-

clase (?), and corroded quartz. The fragments are rounded to subangular fossiliferous limestone, shale, and sandstone. Still farther south the rock is crowded with fragments of limestone, shale, sandstone, chert, and igneous rocks. The matrix is ashy and contains a considerable amount of interstitial calcite.

The area of outcrop is about 2½ miles long and a mile wide and generally is lower than the surrounding area, owing no doubt to the ease with which the rock disintegrates (Pl. 3, fig. 2). The contacts of the agglomerate and surrounding rocks are not well exposed and to some extent show contradictory features. Thus, the syenodiorite porphyry in the larger boundary masses is intrusive into the agglomerate, but the agglomerate contains inclusions of similar porphyry. Likewise some contacts show the agglomerate engulfing rhyolite, although there are many inclusions of rhyolite in the agglomerate. Furthermore there are exposures in which the agglomerate appears to be a contact phase of the rhyolite. Since the agglomerate contains inclusions of so many different sedimentary rocks, is in part tuffaceous, is so much less resistant to weathering, is present in a fault block, is not found in the Cretaceous rocks outside the fault block, and is nearly encircled by igneous rocks, the conclusion is warranted that it occupies a volcanic vent. The surrounding rhyolite may be nearly contemporaneous and may be a part of the vent. The inclusions of syenodiorite porphyry and other igneous rocks were derived from earlier intrusions of these rocks.

A related occurrence is at Mountain 4618 (Pl. 3, fig. 3), which is surmounted by a spinelike peak of rhyolite about 300 feet high. The rhyolite is surrounded completely by material very similar to the vent agglomerate. The sedimentary rocks at the border are Paleozoic. Evidence of the exact character of this occurrence is lacking, but possibly it represents a subsidiary vent and agglomerate contemporaneous with the larger area is intruded by rhyolite.

Rim sill.—The Rim sill extends completely around the dome generally on the lower part of the rim just above the lower part of the Trinity conglomerate. In the southwest and northwest, sills or sill-like masses occur immediately below the conglomerate. In a number of places the sill includes beds of Trinity conglomerate 15 to 50 feet thick, extending several hundred feet along the strike. The sill has been intruded by a plug of soda trachyte at Solitario Peak. The thickness of the sill varies from 15 to 300 feet.

The rock of the sill is white rhyolite varying from spherulitic, partly glassy, to aphanitic; in some places it is slightly porphyritic. The very fine texture prohibits precise classification, but judging from the feld-

FIGURE 1. SOUTHWEST FLANK
Showing steep outward dip of massive Lower Cretaceous limestones (Photograph by Duncan Studios).

FIGURE 2. VENT AREA
Showing lower area of white tuffaceous agglomerate and surrounding wall. View from southeast.

FIGURE 3. OLIGOCLASE-RHYOLITE SPINE
West flank of vent area. Slope is agglomerate.

FIGURE 1. VENT AGGLOMERATE
Incoherent tuffaceous type, northern part of vent area. Exposure 25 feet thick.

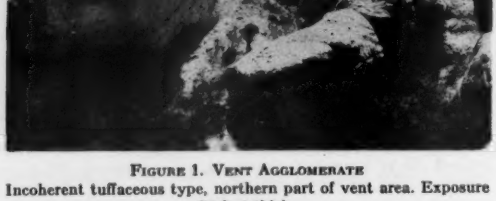

FIGURE 2. VENT AGGLOMERATE
Coarse type with numerous inclusions, central part of vent area.

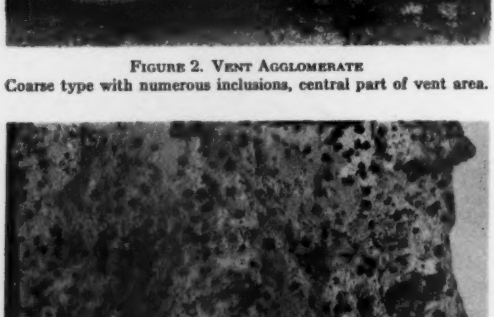

FIGURE 3. PAISANITIC RIEBECKITE SODA RHYOLITE
Coarsest type from Hen Egg Mountain.

spars in coarser specimens the composition appears to vary somewhat. Most determinable specimens are sodi-potassic, but a few may be potassic.

Analcite-syenite plug.—Only one mass of analcite-bearing rock is present in the Solitario, whereas in the area to the east (Pl. 2) literally hundreds of minor intrusions of this kind occur. A few hundred yards west of the central part of the fault block a small oval hill of dark-gray analcitic syenite is associated with syenodiorite porphyry, soda trachyte, and white volcanic agglomerate. The syenodiorite porphyry occurs at the lower west margin of the hill and appears to grade into the analcitic rock which forms the bulk of the mass. A 20-foot dike of soda trachyte, similar to that of Solitario Peak, is traceable westward about 100 yards and is apparently truncated by the syenodiorite porphyry and analcitic syenite. The rock of the hill is extensively jointed, radially and concentrically, and the occurrence appears to be a plug in the flanking Paleozoic rocks.

Igneous sequence and history.—The sequence of igneous rocks in the Solitario cannot be outlined because of lack of contacts and because there are some questionable relations. A general sequence perhaps is as follows:

1. Earlier syenodiorite porphyry	Not seen in place; inclusions in vent agglomerate.
2. Earlier rhyolite	
3. Rhyolite	Rhyolite of Rim sill, main mass of rhyolite of fault block, and other masses. May be contemporaneous with No. 2.
4. Vent agglomerate	
5. Soda trachyte	Intrudes Rim sill at Solitario Peak.
6. Syenodiorite porphyry	Intrudes dike similar to Solitario Peak soda trachyte and the rhyolite of fault block.
7. Plagioclase rhyolite Plagioclase trachyte Late rhyolite (?)	Intrude vent agglomerate.
8. Analcitic syenite	May be contemporaneous with No. 6.

The relations of a potassic rhyolite at East Tank and other masses of similar rocks are unknown except that small dikes in the southern part of the area appear to cut the vent agglomerate.

Although the major intrusive of the Solitario dome, probably a laccolithic mass, remains buried, its presence at depth is stated with confidence. The intrusion of the laccolith was accompanied by the formation of rhyolite of which the Rim sill is an example, though earlier rhyolites and syenodiorites were also intruded. It is impossible to tell whether the extrusive episode of the history occurred concurrently with the major intrusion. The northern extension of the fault-block rhyolite

appears to be a dislocated part of the Rim sill, and if this is so it seems likely that extrusion accompanied the formation of the dome, because the vent agglomerate is closely related to the fault-block rhyolite. Col-

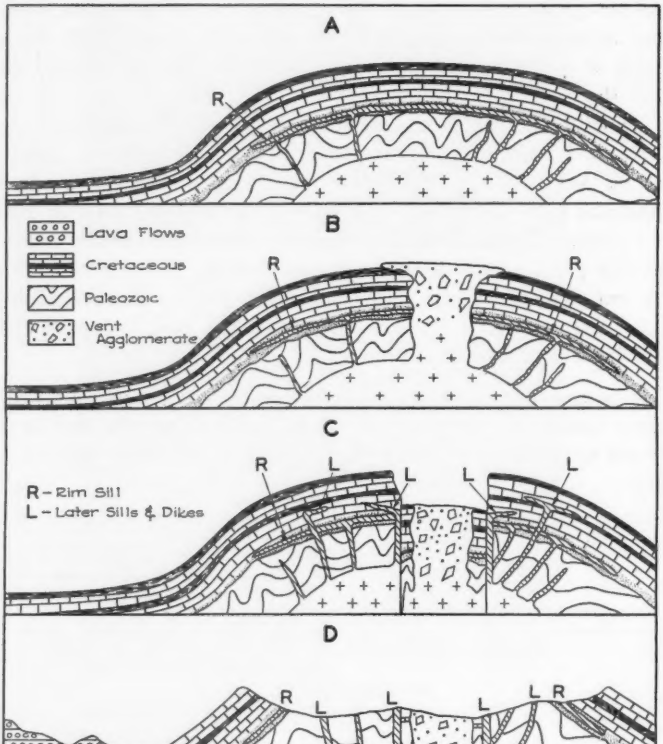

FIGURE 2.—*Diagrammatic cross sections across vent area showing supposed igneous history of Solitario*

A. Initial intrusion of laccolithic mass and Rim sill; B. Breaching of roof in vent area with undetermined amount of extrusion; C. Collapse of roof in vent area and intrusion of later sills and dikes; D. Development of present surface with flanking lava flows.

lapse of the roof of the structure and consequent dropping of the fault block far below its original position followed. Soon after the roof collapse, more basic rocks were intruded into the fault-block rhyolite, the vent agglomerate, and along the fault zones bounding the dropped

block. The Solitario volcano may have contributed lavas to the lava-flow areas to the west, and the lowest lava flow is rhyolitic material similar to the vent agglomerate. However, the lava flows include rocks greatly different from any in the Solitario, and other sources have furnished most of the lava flow material.

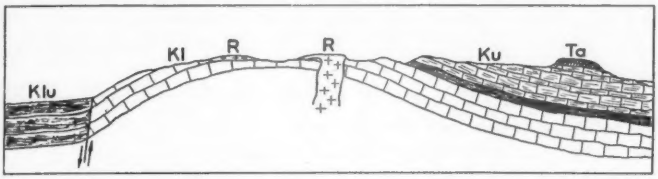

FIGURE 3.—*Diagrammatic cross section of Adobe Walls anticline*
Kl—Lower Cretaceous; Ku—Upper Cretaceous; Klu—Late Upper Cretaceous; R—rhyolite; Ta—trachyandesite.

HIGHER DOMES

General statement.—Next to the Solitario in structural relief are a number of other domes capped by Lower Cretaceous rocks. These appear to be analogous to the Solitario but are smaller and show no evidence of roof collapse or cauldronlike subsidence. They exhibit various features which are believed to give a composite picture of the formation of the Solitario, with the exception of the roof collapse and development of a vent agglomerate.

Without exception these higher structures, including the Solitario, are associated with rhyolites, trachytes, and trachyandesites and show little development of soda-rich or analcitic rocks. The latter are related in origin to lower structures and the sunken block proper.

Adobe Walls anticline.—Midway between Adobe Walls Mountain and Hen Egg Mountain a pronounced anticlinal structure about 1½ miles in diameter (Pl. 2) is quite similar to the Solitario but shows important features not found in the Solitario. The structure is dome-shaped but is cut at the southwest by a fault which brings Late Upper Cretaceous (Aguja) strata in contact with the Buda limestone which is several hundred feet lower stratigraphically. Edwards limestone crops out on the higher and central part of the structure, and around this are circular belts of successively younger formations. A narrow sill of trachyandesite in the Upper Cretaceous strata partly encircles the dome on the north and east. Farther east at a still higher stratigraphic level is a thicker sill of the same rock. Several short dikes, sills, and small pluglike masses are also present on the flanks of the structure. On the

top of the structure a considerable area of extrusive rhyolite rests on an irregular erosion surface on the Edwards limestone and in places occupies valleys in the erosion surface. Flow banding and vesicular structure are common. The base where exposed is a breccia with fragments of Edwards limestone, many of which are rounded. In some places feeder dikes and irregular masses extend downward into the sedimentary rock. Apparently only a small quantity of lava issued from the vents at the top of the dome, for exposures of the material are not found on the flanks.

Except for the fact that erosion has not exposed pre-Cretaceous rocks, this structure is much like the Solitario. If there had been collapse of the roof, the similarity would be very close. It is possible to picture this structure as a small counterpart of the Solitario before the fault block was dropped and before erosion developed the central basin. The age of the erosion surface upon which the rhyolite rests cannot be determined. Lack of erosion in the valleys occupied by lava gives an impression of relatively recent age.

Packsaddle Mountain.—Packsaddle Mountain is a laccolith in which igneous rock has broken through the roof (Pl. 2). It is thus intermediate between such masses as Hen Egg Mountain and Agua Fria Mountain, where the roof has been removed by erosion, and Lion Mountain and the Adobe Walls structure, where only small breaks have been made. The mountain is about 1¼ miles in diameter. As in the Solitario and other similar laccoliths Lower Cretaceous rocks have been elevated to form the crest of the structure with younger formations on the flanks. In the central part of the mountain an irregularly shaped mass of rhyolite has broken through the Lower Cretaceous limestone nearly at right angles to the bedding. On the northwest side a rectangular block of Upper Cretaceous rocks has been pushed up above the Lower Cretaceous limestone. It is possible likewise that peripheral faults exist on the flanks of the structure and that the occurrence is a bysmalith or related form.

Mountain 4318.—Mountain 4318, midway between Packsaddle and Agua Fria, illustrates still another variation in the Solitario type of igneous structure. The mountain is nearly circular, about 1 mile in diameter, and is composed mainly of Lower Cretaceous massive limestone with steep peripheral dips. At the southeast flank a fault brings Late Upper Cretaceous rocks in contact with the Lower Cretaceous. In several places on the top and at the flanks of the mountain irregular rhyolite masses penetrate the limestone almost at right angles. The most striking feature, however, is on the west and northwest flanks,

where a thick sheet of rhyolite lies concordantly between the Upper Cretaceous and Lower Cretaceous rocks (Pl. 5, fig. 1). The sedimentary rocks dip almost vertically near the contact but within a few hundred feet are nearly horizontal. It is possible that the very steep dips were determined by faulting and lifting of the roof of the structure.

Black Mesa dome.—Black Mesa in the south-central part of the area (Pl. 1) is a structural and topographic dome. Near the flanks of the mesa massive Lower Cretaceous limestones are sharply upturned to make the structure, and the change from slight dips to dips of more than 30 degrees occurs in a very short distance. At the northwest and west side of the mountain a roughly circular mass of porphyritic rhyolite, about three-eighths of a mile in diameter, has broken through the limestone much as have the rhyolite masses at Mountain 4318. The igneous rock is sheeted and fractured and at its outer margin has been extensively silicified.

LOWER ANTICLINES

General statement.—In the eastern area (Pl. 2) are many nearly circular anticlinal structures with much lower structural relief than those previously described; some of these contain exposed igneous rocks at the crests. The similarity of all of these suggests igneous intrusion. The sedimentary rocks in these structures are Upper Cretaceous and Late Upper Cretaceous. In most occurrences the slightly more resistant beds of the Upper Cretaceous form the crests and upper flanks of the structures, and the soft clays and marls of the Late Upper Cretaceous group are on the lower flanks.

The igneous rocks of these structures include soda trachyte, syenodiorite, and analcite-bearing rocks. No structure of this kind is known to contain rhyolite or soda-poor trachytic rocks.

Payne's Waterhole anticline.—At Payne's Waterhole in the northeastern part of the area (Pl. 2) an anticline of igneous origin has insufficient structural relief to bring Lower Cretaceous rocks to the surface. This structure is in the middle of the sunken block and is similar to many other structures in the area, though not all of them show exposed igneous rocks at the crests. The anticline is approximately oval at its outer border, but the crest is elongate, forming a sharp ridge. The oldest rocks exposed at the crest are Upper Cretaceous, whereas the flank rocks are Late Upper Cretaceous. At the highest point of the structure erosion has developed a narrow trenchlike valley, in which igneous rocks are exposed. Small sills occur along the flanks just below the crest, and dikes and sills are present at the outer margin. Payne's

Waterhole is a pothole in a small canyon cut across the northwest end of the anticline. Here, too, igneous rock is exposed in the center of the canyon.

Cigar and Leon mountains.—Cigar Mountain and Leon Mountain, northeast of Terlingua (Pl. 2), are separate masses of similar augite-biotite-olivine-analcite syenogabbro. They are thought to be parts of a single original mass cut by Terlingua Creek. The rocks are coarse-grained, and contacts are well exposed. The structure probably is an irregular laccolith with its feeder at the west end of Leon Mountain, which has been faulted and eroded.

Leon Mountain has a steep front along Terlingua Creek with a layer of igneous rock about 400 feet thick. The bottom contact is slightly irregular but generally is concordant with the underlying Late Upper Cretaceous beds. On the north the igneous mass dips at an angle of 30 degrees beneath the overlying baked and indurated sediments. The upper contact of the igneous rock is chilled with fine-grained to aphanitic texture showing veins and pockets of zeolites a few inches in greatest dimension. The main mass of the rock is coarse augite-biotite-olivine-analcite syenogabbro. At the west end of the mountain a small mass of similar rock faulted from the main mass appears to extend downward through the underlying sediments and may have been the feeder.

Cigar Mountain is a roughly circular mass of analcite syenogabbro, three-quarters of a mile in diameter and about 450 feet thick. It is an isolated mass without cover resting concordantly on Late Upper Cretaceous sediments. The analcite syenogabbro is similar to that of Leon Mountain, and in places the marginal facies is fine-grained. Small isolated exposures of fine-grained analcite trachybasalt at the southeast and northwest flanks appear to be marginal facies separated from the main mass by erosion.

Wax factory laccolith.—Near an abandoned wax factory on Fresno Creek, southwest of B. M. 2789, and 2½ miles northwest of Contrabando Mountain (Pl. 1), a laccolith of syenodiorite is unusually well exposed. The original igneous mass was roughly oval about 2 miles in greatest extent with a maximum thickness of 150 feet. Fresno Creek and its tributaries have dissected the mass, exposing all portions of it but leaving intact patches of the roof, which is Upper Cretaceous flaggy limestone. The igneous mass is concordant, and no feeder is exposed unless it be two small dikes of weathered basalt in the bed of Fresno Creek. The mass gradually pinches out so that at the margins it is only a few feet thick. The sedimentary rocks are gently arched over the igneous mass and are slightly baked and indurated.

FIGURE 1. MOUNTAIN 4318
Thick sheet of rhyolite at west flank of mountain with steeply dipping sediments.

FIGURE 2. INDIAN HEAD MOUNTAIN
Uncovered laccolith of soda trachyte flanked by soft Late Upper Cretaceous sediments.

FIGURE 3. HEN EGG MOUNTAIN
Thick bysmalithlike mass of paisanitic soda rhyolite flanked by soft Late Upper Cretaceous sediments.

The main rock of the laccolith is a medium-grained syenodiorite rather poor in mafic constituents. The upper and lower few feet are chilled to fine-grained basalt, but the rest of the rock is quite uniform in texture. Most of the outcrops along Fresno Creek, which is a perennial stream, consist of bright-green, equigranular, medium-grained material. Exposures elsewhere consist of similar brownish rock. The green color of the rock along the stream is due to algal material which has penetrated to a considerable depth, masking the true color of the rock.

Adobe Walls Mountain.—Adobe Walls Mountain in the northeastern part of the area (Pl. 2) and the two mountains immediately south show anticlinal structure, but these do not fit exactly the scheme of classification employed. These masses are soda-rich rhyolites and trachytes of considerable volume and relief. They show flanking, steeply dipping Upper Cretaceous sediments. They are cut by dikes and sheetlike masses of both soda-rich and soda-poor rhyolites and show some evidence of differentiation *in situ*. The oldest strata exposed probably are Boquillas, and only the south flank of Adobe Walls Mountain and the north flank of the mountain to the south show this condition. These structures are apparently at about the same structural level as the Payne's Waterhole anticline and lower than the uncovered laccoliths.

UNCOVERED LACCOLITHS

Agua Fria Mountain, Hen Egg Mountain, Indian Head, Willow Mountain, Sawmill Mountain, and possibly Wildhorse Mountain, Mountain 2661, and Bee Mountain (Pl. 2) are masses of igneous rocks which are not covered by sedimentary rocks and which stand in bold relief above the surrounding country. All are in the sunken block, and all have soft Late Upper Cretaceous rocks around their bases. These mountains are generally oval in plan and range from less than 1 mile to 2 miles in diameter. In all cases the thickness of the igneous rock compared to area is considerable, with a maximum at Hen Egg Mountain and Agua Fria Mountain, where the thicknesses are approximately 800 to 1000 feet (Pl. 5, fig. 3). At these localities the soft flanking rocks and accumulations of talus conceal most of the contacts. In most occurrences, however, limited exposures show that these masses are thick laccoliths or bysmaliths. At the northeast flank of Agua Fria Mountain a block of Upper Cretaceous flaggy limestone has been carried up with the igneous mass to occupy a position above the Late Upper Cretaceous clays and marls. At the south flank of Hen Egg Mountain the sedimentary rocks dip away at an angle of 20 degrees from the igneous mass. At the southeastern flank of Sawmill Mountain a cliff about 70 feet high shows the contact between the igneous and sedimentary rocks.

The soft clays and marls, slightly baked, dip 15 degrees from the igneous mass, but the contact between the igneous and sedimentary rocks is nearly vertical. Somewhat similar conditions exist at the southeast and northwest flanks of Bee Mountain, but the flanking beds at the contact are upturned with a dip of 60 degrees. At the north flank of Indian Head (Pl. 5, fig. 2) rocks belonging to the lower part of the Late Upper Cretaceous division, or perhaps still older, flank the igneous mass with younger rocks cropping out, just beyond.

With the exception of Sawmill Mountain and Wildhorse Mountain the rocks of these masses are soda-rich. The intrusions have penetrated to the level of the very soft Late Upper Cretaceous rock and to positions where the original roofs may have been relatively thin, permitting an accumulation of igneous masses with great thicknesses in proportion to area, with or without faulting. Probably the igneous masses have not been extensively eroded and are present with about their original volumes, revealed by the erosion of the very soft enclosing sedimentary rocks.

DIKES AND SILLS

Dikes and sills are common throughout the region but are most abundant in the southeastern and east-central parts in the deepest part of the sunken block (Pls. 1, 2). They exhibit a considerable range in composition from those of the Solitario which are almost entirely light-colored rocks with no dark or basic varieties and generally thin and short to sills and dikes in the eastern area which are nearly all dark and analcite-bearing. There are a few rhyolitic and trachytic types, and some soda-rich ones, but these are far outnumbered by the darker analcitic rocks which in the field are usually mapped as basalts.

The dikes generally do not exceed 20 feet in thickness, and the average is perhaps 6 feet. A few are as much as 40 feet thick. Most of the dikes are traceable only a few hundred yards, but there are notable exceptions. At Mountain 3513 about a mile northwest of Payne's Waterhole a dike of analcite trachybasalt porphyry 3 feet wide outcrops for more than a mile and cuts the soda trachyte of the mountain. The northwest end of the Payne's Waterhole structure is cut by a dike 3 feet wide of analcite trachydolerite which extends for about a mile with several changes in strike. In the eastern area where these masses are so abundant there are many places where the dikes act as dams across valleys. In such places a waterhole often persists for some time after a rain.

Half a mile west of the Rock Corral on the Alpine road is the only composite dike seen. The rocks in this 30-foot dike are pinkish weathered trachyandesite and olivine basalt porphyry in about equal amounts.

The distribution of the two is not uniform, but in many places the trachyandesite forms the walls, and the basalt porphyry is intrusive into the trachyandesite.

The sills are as abundant as the dikes and show a much greater range in size and composition. A considerable number regarded as sills are 50 to 100 feet thick with much uncovered area. Their occurrence presents the same problem as the thick uncovered laccoliths such as Hen Egg Mountain except that no evidence of displacement of the beds can be found. It is possible that these so-called sills are basal portions of laccoliths. They appear to rest on horizontal or nearly horizontal surfaces and stand in considerable relief above the surrounding country. Mountain 4320, in the northeast part of the area, a flat-topped, steep-sided mass immediately southeast of the Adobe Walls anticline, Mountain 3513, and a mass including Mountain 3505 and Mountain 3429, west of Wildhorse Mountain, are examples of this type in which the rocks are soda rhyolite and soda trachyte. Several masses southwest of Payne's Waterhole appear to be the remnants of a continuous body of this kind composed of analcite-plagioclase syenite.

In the east-central area it is apparent that the analcite-bearing dikes have been feeders for the larger uncovered analcite-bearing sills. The bottoms of the sills are all at higher levels than the present surfaces of the dikes, and many of the rocks are mineralogically alike. However, there are interesting textural differences. The dikes include analcite trachybasalt porphyries with plagioclase phenocrysts up to a centimeter in length and fine-grained equivalents of analcite-plagioclase syenite and analcite syenogabbro.

Feeders of some of the uncovered soda-rich sills have been found. Mountain 3049 immediately south of the Adobe Walls anticline is a horseshoe-shaped mass of soda rhyolite which at one point has been cut by a narrow canyon to levels below the bottom of much of the mass. Here the igneous rocks cut downward across the bedding of the sedimentary rocks. Although not completely exposed, this feeder is tabular, resembling a thick dike.

Smaller sills, from a few feet to about 100 feet in thickness, with covering rocks intact, are numerous throughout the whole region. The most striking of these is the Rim sill of the Solitario, but in the many other laccolithic structures and other folded areas striking masses are found. The Adobe Walls anticline is about half encircled by a sill of trachyandesite. At Payne's Waterhole a sill of analcite trachybasalt porphyry flanks the northwest quadrant of the structure and bifurcates near its southwest end. Two miles north of Payne's Waterhole a sill

20 feet thick of coarse analcite trachydolerite has a V-shaped outcrop due to its position on neighboring flanks of adjacent anticlines.

Study Butte is a soda rhyolite sill several hundred feet thick and has been instrumental in localizing the cinnabar deposits. Just northwest of Bee Mountain three symmetrical parallel ridges are sills, the middle one being analcite-plagioclase syenite, the others soda rhyolite.

PLUGS OR NECKS

A considerable number of small equidimensional more or less pipelike igneous masses occur in the region. Some of these consist largely of igneous breccia or exhibit other features which suggest that they are fillings of feeder channels. Most of these are felsitic, and none can be correlated directly with intrusive or extrusive masses for which they may have been feeders.

One of the most striking of these masses occurs a few hundred yards east of the Alpine road, due south from B. M. 3313 and east of Hen Egg Mountain. It is an elongate oval hill rising 100 feet above the clay flat of Late Upper Cretaceous rocks. The rock is yellowish-white very fine rhyolite whose marginal facies is a breccia with inclusions of sedimentary rock. The mass shows many vertical flow lines. The proximity of this mass to the extrusive rhyolite of the Adobe Walls anticline suggests that the two are contemporaneous. Northwest of this occurrence on the eastern flank of the Adobe Walls anticline are two pluglike masses of similar but unbrecciated rhyolite.

Many other pluglike masses of rhyolite occur. Some of these show significant crossings with other igneous masses. Such masses are found in the northeastern part of the area half a mile east of B. M. 3049 (Pl. 2) where the rhyolite cuts soda rhyolite, 2 miles east and slightly south of B. M. 3049 where the rhyolite cuts soda trachyte and in turn is cut by a dike of analcite trachybasalt porphyry, and half a mile southeast of B. M. 3049 where rhyolite cuts the same mass of soda trachyte. At a locality 2½ miles southeast of B. M. 3049, apparently a circular pluglike mass of later rhyolite cuts analcite-plagioclase syenite.

Two pluglike masses of basic rock have been found. One of these is at Clay Mountain (Black Peak of some maps) west of Terlingua (Pl. 2). Here is an irregularly elongate oval mass of very fine-grained analcitic olivine basalt about an eighth of a mile long and 100 yards wide, the highest point of Clay Mountain being part of the igneous mass. The igneous rock is intrusive into Buda limestone; the contact is nearly vertical, and the limestone shows baking and slight silicification. At the contact, sills 2 to 3 inches thick penetrate the limestone, and veinlets of a white silicate are developed. Margins of the basalt contain inclusions

of the limestone. Near the center of the igneous mass is an area approximately 25 feet in diameter composed of purplish-gray soft volcanic breccia with inclusions of limestone, basalt, and calcite. Near the margin of this area basalt inclusions and the adjoining basalt contain sporadic blebs of black glass. As in the acidic plugs this occurrence cannot be correlated with larger igneous masses.

One and a half miles directly west of Willow Mountain another plug-like mass of basic material 200 yards long and about 75 yards wide stands isolated between dikes of analcite trachybasalt. The plug consists of soft incoherent agglomerate with a reddish matrix containing dark-green altered fragments and cobbles of fine-grained igneous material up to several inches in diameter.

SEQUENCE IN EASTERN AREA

The sequence of intrusion in the area east of the Solitario is difficult to determine because of the great variety of rock, because members of at least two series are present, and because probably some varieties appear more than once in the sequence. Significant crossings which have been found are as follows:

1. Analcite trachybasalt porphyry dike cuts trachyandesite sill southwest of B. M. 3313, northeastern part of area.
2. Analcite trachybasalt porphyry dike cuts rhyolite plug, 2 miles east slightly south of B. M. 3049, on Alpine road.
3. Analcite trachybasalt porphyry dike cuts soda trachyte sill 1½ miles south slightly west of B. M. 3049, at Mountain 3515.
4. Analcite trachybasalt porphyry dike cuts sill of soda rhyolite half a mile east of Mountain 3513 north of Payne's Waterhole.
5. Rhyolite dike or sill cuts soda rhyolite at south flank of Adobe Walls Mountain.
6. Rhyolite dike cuts soda trachyte at south flank, second mountain south of Adobe Walls Mountain.
7. Two rhyolite plugs cut soda trachyte sill 2 miles east of B. M. 3049.
8. Elongate oval mass of rhyolite cuts soda rhyolite sill immediately east of B. M. 3049.
9. Large circular mass of rhyolite cuts soda rhyolite at extreme eastern part of area northeast of Payne's Waterhole.
10. Rhyolite plug cuts (?) sill of analcite trachybasalt porphyry, 2 miles east of Mountain 3513.
11. Trachyte dikes cut sill of soda rhyolite 1 mile directly south of B. M. 3049.
12. Two irregular masses of trachyte cut sill of soda rhyolite half a mile northwest of Bee Mountain.
13. Trachyte cuts soda trachyte, west flank Indian Head Mountain.
14. Intrusion of paisanitic rhyolite of Agua Fria Mountain apparently has deformed analcite trachydolerite sill at south flank of mountain.
15. Analcite syenogabbro cuts paisanitic rhyolite, Mountain 4638.
16. Stringers of analcite syenite cut analcite trachydolerite, 1⅛ miles southeast of B. M. 3049.

17. Analcite-plagioclase syenite cuts analcite trachybasalt porphyry, 1¾ miles north of Payne's Waterhole.

18. Soda rhyolite cuts paisanitic rhyolite at Mountain 4500 and at northwest flank of Adobe Walls Mountain.

The soda-rich felsitic rocks (paisanitic riebeckite soda rhyolite, soda rhyolite) as a group are among the earliest of the intrusives, and the analcite-bearing rocks are among the latest. Nonsodic rhyolites were intruded in at least two periods, one subsequent to the soda-rich felsites and before most of the analcitic group, the other after the intrusion of at least part of the analcitic rocks. The rhyolite at the top of the Adobe Walls anticline probably belongs to the late period. The paisanitic rhyolite of Agua Fria Mountain appears to be younger than the analcite trachydolerite at its south flank, but analcite syenogabbro cuts the paisanitic rhyolite of Mountain 4638. Trachyandesite occupies an intermediate position along with nonsodic trachyte and many rhyolite masses. Among the analcite rocks analcite syenite is the youngest, and limited evidence indicates that analcite-plagioclase syenite is younger than the more femic varieties. The most basic rocks of the area are present in small isolated masses without crossings by other rocks.

The sequence appears somewhat less complicated if it is assumed that two series of rocks were intruded, one related to the Solitario and the other high structures, the other to the sunken block, with the latter generally younger but overlapping to some extent. The abundant analcite rocks in the sunken block suggest very strongly that their intrusion has been controlled by this tectonic feature. Likewise abundant rhyolitic rocks in the higher structures suggest tectonic association or control. The exact place in the sequence and relation of some of the types cannot be determined.

LAVA FLOWS

Extensive lava flows flank the Solitario on the west and north and extend to the southwest and northwest beyond the limits of the area (Pl. 1). They are but the eastern or southeastern edge of a lava field several thousand square miles in area in which sections several thousand feet thick have been noted by Baker (1927, p. 35). The petrology and petrography of the field are only imperfectly known and constitute a major problem in the west Texas igneous area. The present work includes only brief notes on the lavas.

In the eastern area extrusive rocks occur at the Adobe Walls anticline, but these are restricted in area and probably not related to the main mass. Furthermore there are pluglike masses of breccia which may have been feeders to extrusions, but these likewise cannot be related

to the extrusives. To the east in the Chisos Mountain country extrusives are abundant around a center probably localized in the Chisos Mountain uplift.

Sections of the lavas have been studied and samples collected along the edge of the flows at points north of the Solitario, near Rincon Mountain, and southwest of Contrabando Mountain. These localities are spaced at intervals of 7 miles and give a good picture of conditions involved. It does not appear possible to correlate the members in the three sections, and no attempt has been made to trace individual members along the outcrop. In all the sections the bottommost member is a white rhyolitic tuff or tuffaceous conglomerate which overlaps the Cretaceous formations and which in places is underlain by a sedimentary conglomerate unconformably above Cretaceous rocks. Structure in the flows is difficult to see, but north of Rincon Mountain and again north of the Solitario there appears to be a slight peripheral dip from the Solitario. At distances of a few miles from the Solitario the lavas appear to be horizontal or to have dips not related to the structure of the Solitario.

The section at the north flank of the Solitario at the contact of the lava flows with the sedimentary rocks, measured from top to bottom, is as follows:

Unit	Thickness (Feet)
5. Olivine-augite trachyandesite porphyry. Brownish, porphyritic with aphanitic groundmass containing numerous quadratic and lath-shaped feldspar phenocrysts from 15 by 4 millimeters to 5 by 5 millimeters to minute sizes, many with reddish cast, and minute black grains of ferromagnesian minerals. Zoned plagioclase (An_{60} to An_{30}) armored with alkali feldspar, olivine altered to iddingsite, gray augite, brown hornblende ($Z \wedge c = 25°$), magnetite, and apatite in a groundmass of alkali feldspar and oligoclase	20
4. Olivine trachyandesite (mugearitic). Highly vesicular, purplish brown, entirely aphanitic. Vesicles elongated, do not exceed 7 by 3 millimeters and only rarely contain secondary minerals. An aggregate of plagioclase laths, iddingsite after olivine, interstitial alkali feldspar, and dusty apatite	15
3. Vitric rhyolite porphyry. Cream-colored with pronounced flow structure. Differently colored minute flow bands curve around glassy sanidine phenocrysts 1 by 3 millimeters and brownish and cream-colored inclusions 4 by 4 millimeters. A microcrystalline aggregate of alkali feldspar and quartz with minor amounts of glass and bands of spherulites containing phenocrysts of sanidine	15
2. Olivine basalt porphyry. Brownish aphanitic groundmass studded with stubby feldspar phenocrysts averaging 8 by 2 millimeters. Dark grains of ferromagnesian mineral averaging 0.5 millimeter are present as inclusions in the phenocrysts and also in the groundmass. Consists microscopically of phenocrysts of labradorite (An_{54}) with rare rims of alkali feldspar in a groundmass of laths of andesine (An_{46}) augite, iddingsite (?) from olivine, iron ore, needles of apatite, and a little interstitial alkali feldspar	20

Unit	Thickness (Feet)
1. Vitric rhyolite tuff. Composed mainly of rounded to subangular fragments of white to pink vitrophyre 2 to 3 millimeters in diameter, containing minute glassy sanidine crystals and grains, in a matrix largely calcite	20

The section at the west side of the Solitario was taken along a line at the northeast corner of Rincon Mountain and starts in the bed of Fresno Creek where the lower tuff is exposed. The section could be extended westward to include much greater thicknesses of lava. From top to bottom the section is as follows:

Unit	Thickness (Feet)
14. Augite andesite porphyry capping the mountain. Black and porphyritic with aphanitic matrix in which are rare phenocrysts of feldspar 10 by 10 millimeters and abundant smaller ones 3 by 2 millimeters along with sporadic augites 1 millimeter long. Zoned plagioclase (labradorite to andesine) and gray augite ($Z \wedge c = 50°$) in a finer matrix of andesine along with partly altered olivine	65
13. Ashy tuff mainly covered, dark gray, soft	80
12. Augite andesite porphyry. Brownish black, minutely vesicular with aphanitic groundmass in which are numerous weathered feldspar laths (labradorite An_{52}) and plates, maximum size 15 by 8 by 2 millimeters roughly aligned in parallel lines. Stubby augite crystals 2 millimeters long are also visible. Divergent close joints produce nodular and irregular fragments a few inches in diameter. The groundmass is a dense mat of oligoclase laths crowded with augite prisms and grains of iron ore	38
11. Tuff breccia, pinkish to whitish, poorly exposed, forming slope	30
10. Tuffaceous rhyolite. Porphyritic with dense aphanitic partly glassy, reddish-gray matrix in which are numerous sanidine laths 1 by 2 millimeters, and fragments of spongy weathered rhyolite and vesicular basalt up to 5 centimeters	5
9. Tuff breccia, pinkish to whitish, poorly exposed, forming slope	88
8. Augite andesite porphyry. Dove-colored, with aphanitic matrix containing laths of plagioclase (An_{44}) 10 by 3 millimeters, glomerocrysts of feldspar 10 by 8 millimeters, and yellowish-green altered ferromagnesian minerals 4 by 3 millimeters. Exposure shows irregular flow banding, some brecciation, and irregular development of vesicular structure. Groundmass trachytic with laths of oligoclase, grains of augite, iron ore, apatite, and interstitial glass	78
7. Tuffaceous clay. Greenish gray, soft, poorly exposed on slope	72
6. Tuff conglomerate with cobbles of igneous and sedimentary rocks up to 7 centimeters in an ashy matrix	61
5. Tuffaceous clay. Greenish gray soft, poorly exposed on slope	66
4. Vitric rhyolite tuff. Cream-colored friable with harsh feel and ashy appearance. Platy shards of glassy material visible with lens, roughly aligned. Sporadic inclusions of foreign material average less than 3 centimeters. Rounded concretions with calcite matrix up to 3 centimeters. Glassy phenocrysts of sanidine and quartz with film of ashy material. Probably local only	25
3. Trachyte breccia. Light pinkish to gray with dense pinkish matrix enclosing innumerable fragments and pebbles up to 3 centimeters long of a great variety of sedimentary and a few acidic igneous rocks.	

Unit	Thickness (Feet)
Brown chert or flint most abundant sedimentary inclusion. Changes along strike to grayish-green tuff or ash	82
2. Vitric rhyolite tuff. White, harsh, ashy with rough alignment of glassy structures and a very few rounded glomerocrysts to 3 millimeters, unconformable on No. 1	2–15
1. Rhyolitic tuff breccia. Pinkish granular, fragmental with ashy matrix enclosing numerous pebbles and grains of foreign rock material up to 5 centimeters	10

The section southwest of Contrabando Mountain was measured on a mesa, 2.4 miles southwest of B. M. 2662, isolated from the main mass of the flows. This is the most southerly exposure of the flows in the Terlingua-Solitario area. The section from top to bottom is as follows:

Unit	Thickness (Feet)
7. Augite trachyandesite. Brownish gray with aphanitic matrix with a few feldspar glomerocrysts (Andesine An_{35}) up to 3 millimeters and grains of augite ($Z \wedge c = 53°$) to 1 millimeter, forming upper cliffs and benches of mesa. Has xenomorphic granular groundmass of oligoclase and alkali feldspar, altered olivine (?), iron ore, apatite, biotite, and fluorite (?). Brown hornblende ($Z \wedge c = 18°$) is present as reaction rims on augite	175
6. Vitric rhyolite breccia. Pink fine-grained to aphanitic with harsh feel. Contains a very few rock inclusions 5 millimeters in diameter. Matrix is glassy, fragmental, showing collapse and welding	20
5. Tuffaceous conglomerate. Cobbles and pebbles several inches in diameter of massive and amygdaloidal basalt in dense pinkish rhyolite tuffaceous matrix	30
4. Augite trachyandesite similar to No. 7	75
3. Diabasic basalt. Dark gray to black aphanitic with no visible crystal elements; copper stained. Consists of laths of labradorite, augite ophitic to feldspar, partly altered olivine, grains of iron ore, and very small amount of alkali feldspar	175
2. Tuff, reddish to grayish with rounded cobbles and pebbles of chert, limestone, and igneous rock	30
1. Vitric rhyolitic tuff. Fine-grained white to cream-colored with rounded concretionary masses 4 centimeters in diameter, which have calcite cement; contains small inclusions of foreign rock material some of which are rhyolite porphyry. Small areas show glassy shards and flow banding	100

AGE OF IGNEOUS ROCKS

The exact age of the igneous rocks, especially the intrusive rocks, cannot be determined. There is no evidence indicating that any of the rocks are pre-Tertiary. There is some evidence suggesting that most of the intrusives are younger than part of the lavas. The latter have been partly dated through the observations of many geologists beginning apparently with Marcy (1850). A conclusive determination will depend on the discovery of vertebrate fossils in tuff beds in the lavas and on more detailed knowledge of the Tertiary history of Trans-Pecos Texas.

At the present time the lavas as a unit are thought to be older than late Pliocene but to have been extruded through a long time. Part of the intrusive rocks of the Terlingua-Solitario region are younger than part of the lavas because faults associated with the deformation forming the sunken block cut younger lavas. As a group the rocks are probably of early Tertiary age.

PETROGRAPHY

GENERAL STATEMENT

The igneous rocks of the region include so many varieties that detailed description and exact classification of all of them are impracticable. In this paper the rocks with the exception of the lavas are grouped into larger divisions which include varying but related types. The lava flows are excluded because only their eastern margin has been studied and because their relation to the intrusive rocks is not yet known. The most significant grouping is into analcite-bearing rocks and those without analcite. In the latter group the most important general types, disregarding textural modifications, are rhyolite to leucorhyolite rich in alkali feldspar, soda rhyolite rich in soda amphibole or pyroxene, trachyte, soda trachyte, syenodiorite-trachyandesite, and basalt. The analcite-bearing rocks constitute a series with analcite syenite, analcite syenodiorite, analcite syenogabbro, analcite trachybasalt, analcite trachydolerite, and teschenitic analcite gabbro as important members. They form at least half of the mappable masses, though many are smaller dikes.

Nearly all types range in texture. Among the nonanalcitic rocks the principal modification is to porphyritic varieties. Fine-grained phanerites are rare. Among the analcitic rocks there are several medium- to coarse-grained phanerites, many porphyritic varieties, and a few which are truly aphanitic. The rocks of the region as a unit are typically hypabyssal.

RHYOLITIC ROCKS

General statement.—Nonsodic rhyolitic rocks are abundant in the Solitario, are present in a good many dikes and pluglike masses in the area to the east, and constitute parts of the lava flow series in the extreme western part of the area. A considerable number of types are included under the rhyolite symbol on the maps (Pls. 1, 2), and probably a series of chemical analyses of the very fine-grained ones would reveal variations not now recognized. Many of the rocks are very fine-grained aggregates of alkali feldspar and quartz with only traces of other minerals. They range texturally from breccias and glasses through spherulitic types to porphyritic rocks. A number of the rocks included contain both potash feldspar and sodic plagioclase along with mafic minerals

and are given a distinctive symbol on the map of the Solitario. In general the rhyolites of the Solitario are finer-grained and contain more quartz than those of the eastern area.

The three analyzed specimens (Nos. II, IV and VI, Table 17) show the major ranges in composition of the rhyolites. In one potash greatly exceeds soda, in another the two constituents are more nearly equal, while in the third soda slightly exceeds potash, alumina is high, and silica low. The latter is representative of the plagioclase-bearing type. It is difficult or impossible to correlate many of the fine-grained rhyolites with these analyses, but most of the rocks probably are similar chemically to the first type, and only a few correspond to the third type.

Potassic rhyolite.—The analyzed specimen is from the irregular sill-like mass which extends westward from East Tank in the Solitario. The rock is cream gray with an aphanitic groundmass in which are many phenocrysts of quartz and feldspar averaging about 1 millimeter in greatest dimension. The groundmass is a granular aggregate of quartz grains, alkali feldspar grains, and laths whose average size does not exceed 0.01 millimeter. The quartz phenocrysts are nearly as abundant as feldspar and are partly euhedral quartzoids and partly embayed and corroded. The feldspar phenocrysts are orthoclase (negative, large 2V) with Carlsbad twinning with limited very fine intergrowths of albite. There are no discernible mafic minerals, but sections are dusted with specks and rods of opaque material.

A considerable number of rhyolites in the Solitario and also in the eastern area are so similar microscopically to the analyzed potassic rhyolite that they are thought to be essentially similar. In these rocks there is a tendency toward a granular or granophyric or micropoikilitic groundmass, and quartz appears not only in the groundmass but also as phenocrysts along with feldspar. The groundmass does not contain notable amounts of plagioclase. In some specimens the groundmass is dense microcrystalline or even partly glassy, but even there the quartz phenocrysts are prominent. Some specimens contain a little biotite, but mafic minerals generally are present only as traces or are represented by minute dustlike opaque material. Some specimens contain a spherulitic groundmass in which spherulites of feldspar are prominent. In the Solitario prominent masses of this type are as follows:

1. Dikelike mass 1 mile southwest of Lefthand Shutup.
2. Sill near East Tank.
3. Series of small pluglike masses due south of East Tank.
4. Irregular pluglike mass three-fourths of a mile northwest of B. M. 5048.
5. Several sills and dikes east of Fresno Creek along west and northwest flank of Solitario.

6. Sills at Contrabando Mountain.
7. Mass at Black Mesa.

In the eastern area rhyolites of this type are present on the anticline west of Adobe Walls, in an elongate thick dikelike mass 1½ miles south of Mountain 3518, in a sill at the west flank of Agua Fria Mountain, and in a small plug three-fourths of a mile south of B. M. 3313.

Mountain 4318 in the northern part of the area (Pl. 2) contains several masses of rhyolite differing somewhat from the potassic type. The entire west flank of the mountain is composed of a thick sill-like mass dipping steeply away from the mountain and cutting the sedimentary rocks at a small angle. The rock is light gray porphyritic with an aphanitic, slightly vesicular groundmass in which are abundant phenocrysts of quartz and glassy feldspar and also a few inclusions of a light-colored felsitic rock. The groundmass consists of closely packed laths of alkali feldspar averaging 0.1 by 0.015 millimeter in a mat of interstitial quartz. The feldspar phenocrysts are soda orthoclase (negative, extinction = 0° on 001 and 11° on 010, and $\gamma = 1.528$) both untwinned and in Carlsbad twins tending toward quadratic habit. The less abundant quartz phenocrysts are corroded. Accessory minerals include needles of apatite, a very little purple fluorite, sphene (?), and rare grains of iron ore. Small irregular masses of generally similar though finer-grained rhyolite have broken through the roof of the mountain.

Sodipotassic rhyolite.—The analyzed specimen of sodipotassic rhyolite is from a small irregular intrusive mass in the southwest-central part of the Solitario. The rock is cream-colored aphanitic with rare scattered pinkish feldspar phenocrysts up to 1.5 millimeters long. The groundmass includes cloudy stubby laths of orthoclase (extinction = 0° on 001) and slender laths of albite (extinction = 18° on 010) 0.15 by 0.05 millimeter with albite twinning. Some of the albite laths are in stellate groups. The phenocrysts are altered but appear to be fine perthitic intergrowths of albite and orthoclase. Quartz is partly interstitial but mostly discrete grains averaging 0.07 millimeter.

This type of rhyolite appears to be almost entirely restricted to the Solitario. A flanking sill-like sheet at the south flank of Adobe Walls Mountain is the only rock in the eastern area microscopically similar to the analyzed specimen. In the southern and eastern part of the Solitario several masses appear to be similar to the analyzed specimen. Two of these are dikelike masses cutting the vent agglomerate. In all these rocks plagioclase, either albite or albite-oligoclase, is present along with potash feldspar. The phenocrysts are intergrowths of the two minerals, and

both are present in the groundmass. Some specimens contain traces of biotite, apatite, and zircon.

The main mass of Wildhorse Mountain is a distinctive biotite-augite granophyre. The rock has a lilac-gray aphanitic groundmass enclosing

TABLE 2.—*Modes of rhyolitic rocks*

(Volume percentages)

	1*	2*	3	4*
Quartz	4.9P	8.0	5.0	3.9
Quartz-feldspar groundmass	82.1	.....	.....	38.0
Alkali feldspar	13.0P	92.0	.....	.....
Sanidine	.....	.....	.....	34.9
Anorthoclase	.....	.....	88.1	.....
Albite-oligoclase	.....	.....	.....	20.0
Biotite	.....	.....	.....	1.6
Augite	.....	.....	.....	0.8
Iron ore	.....	.....	6.9L	0.8
Apatite	.....	.....	.....	+
Zircon	.....	.....	+	.....

L = Includes magnetite and secondary limonite.
P = Phenocrysts or discrete grains.
* = Analyzed specimen.
+ = Trace.

1. Potassic rhyolite, East Tank Solitario.
2. Sodipotassic rhyolite, southwestern part, Solitario.
3. Rhyolite, Packsaddle Mountain.
4. Biotite-augite granophyre, main mass, Wildhorse Mountain.

numerous phenocrysts of feldspar and biotite. The feldspars are in equidimensional to rounded glomerocrysts 1 centimeter in diameter and glassy laths 3 millimeters long. Flakes and shreds of biotite up to 3 millimeters long are rather uniformly distributed, and some of these are enclosed in the feldspar phenocrysts.

Under the microscope (Pl. 6, fig. 1) the rock shows a strikingly granophyric groundmass, with two generations of feldspar phenocrysts, the smaller of which really are microphenocrysts. The groundmass consists of optically continuous areas of quartz 0.15 millimeter in diameter, in which are distinct, slightly divergent laths of alkali feldspar averaging 0.015 millimeter long. Most of the larger phenocrysts of feldspar are glomerocrysts composed of anhedral crystals averaging 0.6 millimeter in greatest dimension. A few of these individual grains contain cores of oligoclase (An_{29}) (negative; extinction = 11° ⊥ to 010) with albite and

pericline twinning surrounded by albite or more rarely by orthoclase. Most of them are albite (positive; extinction = 13° on 010, and $\gamma = 1.538$) with fine albite twinning or sanidine (2V small; extinction = 0° on 001 and 5° on 010). A few are perthitic intergrowths of albite and orthoclase. Individual smaller phenocrysts of the several types are present, but sanidine laths averaging 0.15 by 0.1 millimeter are most abundant. Among the smaller phenocrysts (microphenocrysts) are abundant laths in which the ratio of length to width is 2:1.5, averaging 1.25 millimeters long, with Carlsbad twinning in which albite is intergrown in minute rods normal to the elongation of the laths. The host is the potash feldspar with extinction angles of 10° on (010) and 0° on (001) and probably is soda sanidine. The biotite crystals are corroded and resorbed, with the reaction ranging from a rim of magnetite grains to aggregates of completely altered biotite. Augite ($Z \wedge c = 46°$) is greenish gray in smaller crystals averaging 0.1 millimeter long, and in a few phenocrysts up to 1.6 millimeters. Some of these along with the biotite are at the centers of the glomerocrysts of feldspar. Iron-ore grains not associated with alteration of biotite are sparingly present up to 0.4 millimeter long. There are a few minute prisms of apatite frequently enclosed in augite and rarely larger grains of quartz distinct from that of the groundmass.

Quartz-bearing rocks somewhat similar to the granophyre of Willow Mountain are present in the Solitario. One such rock is in the narrow dikelike mass forming part of the east flank of the vent area. It is oligoclase rhyolite porphyry with a fine-grained to aphanitic groundmass containing feldspar phenocrysts up to 1.5 by 1.2 centimeters. The groundmass is an exceedingly fine aggregate of intergrown alkali feldspar and quartz with a few distinct needles of alkali feldspar 0.03 millimeter long and a few discrete grains of quartz up to 0.07 millimeter. The largest feldspar phenocrysts are glomerocrysts which consist of grains of sanidine and albite sometimes enclosing cores of oligoclase (An_{16}). Smaller feldspar phenocrysts include perthitic intergrowths of albite and orthoclase and separate laths of sanidine. Corroded anhedral quartz phenocrysts are smaller than the feldspar (1.7 by 1.5 millimeters). Biotite often replaced by iron ore is abundant; zircon and apatite are rare. Notable amounts of secondary calcite are present, in some cases six-sided pseudomorphs after amphibole (?). This rock is within the boundaries of the mass mapped as syenodiorite porphyry from which an analyzed specimen was collected. Apparently it constitutes a minor part of the main mass but is not separable in the field. Its affinity to the syenodiorite porphyry is seen in the character of the feldspar and in the mafic constituents.

West of this locality a dike of somewhat similar rock cuts the vent agglomerate, and north along the eastern border of the vent area is a small mass of the rock, just east of Mountain 4945, associated with the fault. At the latter place the rock is still more basic since cores of some of the armored phenocrysts are as basic as andesine (An_{38}). This rock also contains biotite, iron-ore grains, very small amounts of gray-zoned augite ($Z \wedge c = 38°$), and possibly a trace of brown hornblende. The rock is transitional toward some of the trachyandesites of the area.

A quartz-poor rhyolite forms the igneous core of Packsaddle Mountain (Pl. 2). The rock is gray and fine-grained, showing small dark euhedral outlines of a mafic mineral replaced by limonite and a few feldspar phenocrysts up to 3 by 2 millimeters. The phenocrysts grade downward to groundmass feldspar which averages 0.2 millimeter. The phenocrysts are anorthoclase (2V medium to small; extinction = 10° on 010), some with obscure gridiron twinning. The groundmass laths show Carlsbad twinning but appear to be similar to the phenocrysts. The areas of limonite in the section evidently are from some mafic mineral, and some show outlines suggestive of hornblende. Magnetite is rather abundant, and there are a very few minute crystals and grains of zircon. Quartz is interstitial and difficult to measure in a volumetric analysis. An average of several traverses gave 5 per cent, which may be a minimum figure. Certainly the rock is close to the border line between trachyte and rhyolite.

SODA RHYOLITE

Rhyolite with notable quantities of one or more soda-bearing mafic minerals is very abundant in the eastern area but is only scantily developed in the Solitario. The feldspars of these rocks do not differ markedly from the nonsodic rhyolite except that anorthoclase is more common, but the presence of sodic amphibole and pyroxene gives them a distinctive character. Most of these rocks are aphanitic with feldspar phenocrysts, and the presence of the greenish mafic minerals imparts a grayish-green color to the rocks. Weathering produces yellowish-brown to cream colors similar to those of the nonsodic rhyolite. The rocks are similar to soda trachyte in hand specimen because quartz is hidden in the groundmass. Varieties recognized are classified on the basis of mafic mineral, feldspar, and to some extent texture.

The soda rhyolite from the mountain immediately south of Adobe Walls Mountain is aegirite-augite soda rhyolite with phenocrysts of perthitic albite and orthoclase. The rock is light gray and somewhat vesicular, and mafic minerals are partly weathered to brown iron oxide. The abundant feldspar phenocrysts consist of clusters of laths and indi-

vidual crystals with an average size of 3 by 2 millimeters. The groundmass is mainly subhedral to irregular feldspar laths 0.15 by 0.04 millimeter. The laths are soda orthoclase (extinction = 0° on 001 and 10° on 010) with Carlsbad twins; they are also intergrown with albite which appears as minute peg-shaped areas extending inward normal to the elongation of the laths. Rounded prismatic green grains of aegirite-augite are slightly pleochroic with extinction angle of 38 degrees. The average size is 0.07 millimeter, but rarely the mineral forms microphenocrysts 0.2 millimeter in cross section. Minute iron-ore grains are present and rarely grains of purple fluorite. Quartz is interstitial. The border facies of this mass approaches trachyte in composition and consists of an exceedingly fine aggregate of alkali feldspar laths with a little interstitial quartz and rare soda orthoclase phenocrysts and glomerocrysts; mafic minerals are virtually absent, though sections are dusted with minute dark materials. There is a very small amount of interstitial quartz. Another variation in the rock contains abundant interstitial quartz, spongelike aggregates of limonite pseudomorphous after mafic minerals, and perthitic phenocrysts with perhaps some anorthoclase.

Adobe Walls Mountain is composed of a distinctive riebeckite-aegirite soda rhyolite. The mass is a conical-shaped peak 900 feet high, a laccolithic intrusive. The enclosing sedimentary rocks are the soft Late Upper Cretaceous rocks, but flanking the mountain on the northwest a narrow band of older sediments dips steeply northwest. There is some variation in the rock, and the mass is mapped as paisanitic rhyolite. The most abundant type from the central part of the mass has a light grayish-green aphanitic matrix in which are numerous weathered, stubby, lath-shaped feldspar phenocrysts 2 millimeters long. Mafic minerals appear as minute dark specks in the matrix. Another type is much darker green, with more abundant mafic minerals in larger grains. A third type is distinguished by abundant glomerocrysts of weathered feldspar up to 0.6 millimeter across. The matrix consists of irregular laths of cloudy, partly weathered alkali feldspar averaging 0.15 millimeter in length; anhedral, generally equidimensional grains of quartz 0.1 millimeter in diameter, often poikilitic to the other minerals; prismatic grains of aegirite ($X \wedge c = 4°$) pleochroic in shades of deep green and yellow-green averaging 0.1 millimeter long; and irregular areas of limonite from the alteration of riebeckite. A very few irregular shreds of riebeckite are present, some of which are partly altered to limonite. The feldspar phenocrysts are stubby laths with Carlsbad twinning and are cloudy through alteration. They are orthoclase (2V large; extinction = 6° on 010) slightly perthitic with albite, the latter forming irregular minute

branching areas. The groundmass feldspar appears similar to the phenocrysts.

A dike 16 feet wide extending southeast from the southeast flank of Mountain 4320 is aegirite soda rhyolite with a granophyric groundmass. The rock is light bluish gray with an aphanitic groundmass in which are numerous glassy feldspar phenocrysts and glomerocrysts up to 2.5 millimeters across. The groundmass consists of unoriented stubby laths of alkali feldspar, some with Carlsbad twinning, and averaging 0.15 millimeter in length, in a very fine granular quartz base. Most of the groundmass is granophyric, though it varies in different areas. Green aegirite in ragged prismatic grains averaging 0.07 millimeter long is the main mafic mineral. A very few grains of the mineral are subhedral microphenocrysts up to 0.2 millimeter in length. Minute iron-ore grains and purple fluorite grains also are present in the groundmass. The feldspar phenocrysts are colorless unaltered anorthoclase (2V moderate; faint gridiron twinning) with inclusions of aegirite and frequently with a narrow border zone lined with minute grains of the pyroxene and iron-ore grains.

Mountain 4320 in the northeastern part of the area (Pl. 2) is an uncovered sill several hundred feet thick resting on Late Upper Cretaceous beds which show no local deformation. The igneous mass is separated from another similar mass to the east (beyond the mapped area) by a narrow erosion gap, and the two were probably once continuous. The rock shows some variation, but the most abundant type is grayish-green aegirite-augite soda rhyolite with a fine to aphanitic groundmass in which are numerous phenocrysts and glomerocrysts of glassy feldspar. Individual phenocrysts are laths up to 3 millimeters in length. Many of the glomerocrysts contain inclusions of minute grains of mafic minerals. Weathering of the mafic constituents imparts a brownish cast to some areas of the rock.

The feldspar of the glomerocrysts is mainly anorthoclase (2V moderate; extinction $= 11°$ on 010, and $\gamma = 1.528$) in anhedral quadratic grains, many of which show faint gridiron twinning. These contain aegirite-augite inclusions up to 0.8 millimeter long, and some show a narrow rim of minute grains of this mineral. Lath-shaped separate phenocrysts with Carlsbad twinning probably are sanidine (2V small). Aegirite-augite ($X \wedge c = 34°$) slightly zoned is present as rare microphenocrysts of the same size as the inclusions of the mineral in feldspar. The mineral is also abundant in the groundmass in minute, ragged prismatic grains. The greater part of the groundmass is an aggregate of feldspar laths and anhedral grains in a base of quartz, the complete aggregate having a granophyric aspect. The feldspar laths show Carlsbad twinning

and average 0.16 millimeter long. Some of them show an almost submicroscopic intergrowth with albite (?) in spindles normal to the sides of the laths. The groundmass laths probably are soda orthoclase since they show extinction angles up to 10 degrees.

A small uncovered sill between Yellowjacket Spring and Mud Spring in the eastern part of the area consists of weathered quartz-poor soda rhyolite or microgranite of distinctive texture. The analysis of the rock (No. IX, Table 17) does not give an accurate picture of its original composition because all the mafic minerals have been altered to limonite with a consequent elimination of silica. Since the original mafic constituents totalled nearly 15 per cent, the unaltered rock was considerably richer in silica than is indicated by the analysis. The rock is brownish lavender, fine-grained, nearly equigranular, with rare slender laths of feldspar up to 3 millimeters long. Under the microscope it shows a groundmass of broad feldspar plates, irregular, ragged prismatic areas of limonite pseudomorphous after mafic minerals, and irregular myrmekitelike areas of quartz interstitial to the feldspar. Sporadic irregularly quadratic and lath-shaped feldspar phenocrysts are also present. The groundmass feldspar is soda orthoclase (extinction = 0° on 001 and 13° on 010) in stubby laths with Carlsbad twinning and averaging 0.3 by 0.15 millimeter. The feldspar phenocrysts are irregular laths up to 3 millimeters long. They include anorthoclase (2V medium; extinction = 10° on 010, and $\gamma = 1.529$) and rarely albite (n—Canada balsam, positive) with rare albite twinning. It is possible that a little albite is present among the groundmass feldspars. Some of the groundmass feldspar laths show myrmekite fringes of quartz, and these grade into interstitial areas up to 0.5 by 0.3 millimeter. Quartz also is present in anhedral grains and to a limited extent as an interstitial material without special textural features. The mafic minerals are completely weathered to limonite pseudomorphs which have the habit seen in aegirite-augite of many of the rocks of the area. Rare minute grains of purple fluorite are present in the sections.

An anticlinal structure three-fourths of a mile northeast of Payne's Waterhole, generally similar to the structure at the latter place, contains soda rhyolite at its crest. The rock is grayish lavender with an aphanitic groundmass in which are glassy and also chalky feldspar phenocrysts up to 2 millimeters long. At contacts the rock is slightly vesicular. The trachytic groundmass contains well-oriented feldspar laths and mafic elements. The feldspar consists of laths 0.08 millimeter long, many with Carlsbad twinning. The mafic mineral grains are very abundant (16.4 per cent) as stubby prismatic grains generally shorter than the feldspar laths. The mafic elements are partly altered to iron oxide, but un-

altered grains are riebeckite. Quartz is virtually absent from the groundmass but is present in larger anhedral grains up to 0.5 millimeter in diameter. Most of the feldspar phenocrysts are glomerocrysts composed of several individuals. Most of these are clear Carlsbad twins of orthoclase.

The rock of the main mass of Willow Mountain is a quartz-poor soda rhyolite rich in mafic constituents with clear phenocrysts and glomerocrysts of soda-rich sanidine. The rock is dark greenish gray with an aphanitic groundmass. The prenocrysts enclose visible dark grains of mafic minerals, in grains of a size rarely present in the groundmass. The feldspar phenocrysts are Carlsbad twins and untwinned laths with rarely an obscure albitelike twinning. Laths average 1.5 by 0.8 millimeter, but glomerocrysts reach 4 millimeters in diameter. Crushed fragments show the mineral to be soda sanidine (negative, 2V small; extinction $= 0°$ on 001 and $10°$ on 010; $\alpha = 1.522$, $\gamma = 1.528$). Rare microphenocrysts of green-brown aegirite-augite ($X \wedge c = 32°$) are present frequently as inclusions in the feldspar phenocrysts. The groundmass consists of soda orthoclase (extinction $= 6°$ on 010 and $0°$ on 001; $\alpha = 1.522$, $\gamma = 1.527$) in Carlsbad twins averaging 0.12 by 0.06 millimeter, anhedral quartz grains, and interstitial quartz along with abundant ragged prismatic grains, 0.08 by 0.03 millimeter, of aegirite-augite similar to that of the microphenocrysts. There are rare grains of iron ore and of pyrite.

The thick dikelike sill at Study Butte has been mentioned in most accounts of the quicksilver deposits of the Terlingua district because mining operations have been carried on to produce cinnabar found within and at contacts of the mass. Hill (1902) and Udden (1918) described the occurrence in connection with the ore deposits. The igneous mass is 400 feet thick and dips at about 45 degrees southwestward so that its steep face forms the rim of the butte. The sediments intruded are the soft Late Upper Cretaceous marls so that structural conditions are not well exposed. Data secured from mining operations by Udden and during the present work indicate that the mass cuts across bedding planes to some extent. A small exposure to the east is of similar rock. It has been described as andesite and rhyolite but appears to be a quartz-poor soda rhyolite or microgranite in which the mafic minerals have been replaced by pyrite and to some extent by cinnabar. In the sections the mafic minerals are entirely replaced, but the shapes and habits of the pseudomorphs suggest strongly that the minerals originally were sodic pyroxene or amphibole. The rock is gray with a fine-grained groundmass in which are sporadic feldspar phenocrysts up to 4 millimeters long. The groundmass is composed of unoriented laths of feldspar with Carlsbad twins up to 0.3 millimeter long, a little interstitial quartz, and

TABLE 3.—*Modes of soda rhyolite*

(Volume percentages)

	1	2	3	4	5	6	7	8*	9	10
Quartz	16.4	16.0	12.9	11.1	10.5	12.0	6.4	5.4	5.4	5.0
Alkali feldspar	.....	.....	81.1	.....	.....	.....	.....	.....	.....	.....
Orthoclase	+P	69.5	.....	.....	.....	73.8	.....	.....	78.2	.....
Soda orthoclase	81.2	.....	.....	78.7	79.5	.....	82.0	80.3	.....	76.0
Anorthoclase	.....	.....	+P	+P	+P	.....	.....	+P	.....	.....
Sanidine	.....	.....	.....	+P	+P	.....	.....	.....	.....	.....
Albite	+I	+I	.....	+?	+?	+I	.....	+P	.....	.....
Aegirite	.....	11.5	6.0	.....	.....	10.2	.....	.....	.....	.....
Aegirite-augite	1.4	.....	.....	10.2	10.0	.....	11.6?	14.3I	.....	19.0
Riebeckite	.....	3.0	.....	.....	.....	4.0	.....	.....	16.4	.....
Iron ore	1.0	.....	+	.....	.....	.....	.....	.....	.....	.....
Fluorite	+	.....	+	.....	.....	.....	+	+	.....	.....

P = Phenocrysts included with other feldspar.
I = Intergrown with potash feldspar.
L = Altered to limonite.
* = Analyzed specimen.
+ = Trace.

1. North flank of mountain immediately south of Adobe Walls Mountain.
2. Adobe Walls Mountain.
3. Dike southeast of Mountain 4320.
4. Mountain 4320.
5. Mountain 4320.
6. Adobe Walls Mountain.
7. Study Butte.
8. Southeast of Yellowjacket Spring.
9. 1 mile southeast of Mountain 3513.
10. West flank of Willow Mountain.

the replacement products of the mafic minerals. Both the phenocrysts of feldspar and the groundmass laths are soda orthoclase (2V large; extinction = 12° on 010).

Paisanitic riebeckite soda rhyolite and textural and mineralogical modifications occur as the most abundant types in Agua Fria Mountain, Mountain 4302, Mountain 4638, Mountain 4500, and Hen Egg Mountain. A considerable part of Adobe Walls Mountain likewise is composed of this rock. A sill 15 feet thick immediately east of Mountain 4500 and a dike at the northwest flank of Hen Egg Mountain also are of this material. Agua Fria Mountain and Hen Egg Mountain are among the thickest masses of igneous rocks in the region and are deroofed intrusives which penetrated to the soft Late Upper Cretaceous beds. At the former mountain, locally, the sediments show steep dips away from the intrusive, and at the northeast flank a block of Upper Cretaceous limestone has been carried up with the igneous mass far above its normal position. The other mountain masses do not show plain relations, but at most of them, locally, the sediments dip sharply away from the intrusives.

The texture and mineralogy of the several rocks vary somewhat. Many of them are similar to paisanite described originally by Osann (1893) from a locality about 80 miles to the northwest. Specimens from Hen Egg Mountain and the sill are especially striking because they possess a light-gray uniform groundmass through which are distributed rounded blue-black unusually large grains of riebeckite (Pl. 4, fig. 3). Specimens from Agua Fria likewise are comparatively coarse, but riebeckites are elongated and dendritic, with a distinct flow structure. Similar structure is present in marginal facies of Adobe Walls Mountain. In some localities (Mountain 4638, the sill, and the dike) the bulk of the rock is aphanitic, and the riebeckite grains are minute, barely visible to the unaided eye. In these localities the groundmass is darker, approaching a blue gray. Marginal facies at most localities are finer-grained and distinctly darker. Microscopic examination shows that the marginal types contain more riebeckite and notable amounts of aegirite or aegirite-augite. Porphyritic types with feldspar phenocrysts are common, but the phenocrysts are small (average 1.5 millimeters). In all specimens sporadic phenocrysts of this kind are found. Most of the riebeckite grains are not phenocrysts, strictly speaking, but poikilitic aggregates (Pl. 6, fig. 2) enclosing other minerals. The dike contains composite materials in which dense aphanitic gray rock alternates with streaks and patches of lighter-colored coarser material in which the riebeckite grains are 2 millimeters in diameter. The dike is 20 to 70 feet thick and extends from Hen Egg Mountain to Mountain 4638. Possibly it was a feeder to the two mountain masses.

TABLE 4.—*Analyses of paisanitic riebeckite, soda rhyolite, and related rocks*

	1	2	3	4	5
SiO_2	76.71	75.53	74.35	73.35	74.19
Al_2O_3	12.15	12.26	12.82	14.38	12.85
Fe_2O_3	0.94	1.56	1.37	1.96	1.60
FeO	0.60	0.73	0.82	0.34	0.98
MgO	0.18	0.07	0.16	0.09	0.11
CaO	0.05	0.16	0.14	0.26	0.12
Na_2O	4.73	5.24	5.19	4.33	5.86
K_2O	3.88	4.05	4.36	5.66	3.98
H_2O+	0.31	0.00	0.17	.....	0.10
H_2O-	0.11	0.13	0.06	.....	0.16
TiO_2	0.09	0.10	0.14	.....	0.09
P_2O_5	0.02	0.01	0.02	.....	tr.
	99.77	99.84	99.60	100.37	100.04

Norms

	1	2	3	4	5
Q	34.68	30.06	27.48	25.86	25.50
or	22.80	23.91	25.58	33.36	23.35
ab	39.82	40.35	41.39	36.68	44.01
an	0.28	.....	.....	1.39	.....
di	.....	0.46	.....	.....	0.43
hy	0.66	0.66	1.19	0.20	0.10
C	.....	.....	.....	0.61	.....
acm	.....	.....	2.31	.....	4.62
il	0.15	0.15	0.15	.....	0.15
mt	1.16	0.70	0.93	1.16	.....
ap	.....	.....	0.34	.....	.....
hm	.....	.....	.....	1.12	.....
ns	.....	.....	.....	.....	1.34

1. Paisanitic riebeckite soda rhyolite, east of Mountain 45.00. R. B. Ellestad, analyst.
2. Paisanitic riebeckite soda rhyolite, Mountain 4500. R. B. Ellestad, analyst.
3. Paisanitic riebeckite soda rhyolite, Mountain 4638. R. B. Ellestad, analyst.
4. Paisanite, Mosquez Canyon, Apache Mountains. A. Osann, analyst.
5. Riebeckite soda granite porphyry, San Francisco Mountain, Arizona. H. H. Robinson, analyst.

The groundmass usually is imperfectly granophyric. In the dike the groundmass of the finer-grained material is microfelsitic and contains possibly a little glass. The rock from the sill contains spherulites

of feldspar and quartz averaging 0.2 millimeter, along with areas of granophyric texture. In the coarser types from Agua Fria and Hen Egg the granophyric character is not so pronounced, and in specimens from Adobe Walls Mountain it is not apparent. Specimens from Mountain 4500 show a groundmass partly granophyric and partly xenomorphic granular (grains 0.02 to 0.15 millimeter). Agua Fria and Adobe Walls Mountain show a decided trachytic arrangement of groundmass materials superimposed on the granophyric elements.

The phenocrysts are mainly feldspar, although some specimens contain sporadic quartz phenocrysts. The maximum size is 2 millimeters in greatest dimension, but there is generally a seriate range down to sizes only slightly larger than the groundmass. The feldspar phenocrysts are quadratic crystals of anorthoclase (2V moderate; extinction $= 9°$ to $11°$ on 010, and $\gamma = 1.529\pm$) with a very fine gridiron twinning or with Carlsbad twins or laths probably of the same mineral. Rare phenocrysts were tentatively identified as albite. In nearly all specimens, the lath-shaped feldspar and some of the equidimensional grains show microperthitic intergrowths with albite arranged nearly normal to the elongation of the crystals.[1] This feature likewise is present in the minute feldspar laths of the groundmass. The groundmass feldspar is classified as alkali feldspar but probably is mainly anorthoclase since it exhibits a large extinction angle and $\gamma = 1.528$.

Riebeckite occurs as spongelike crystals with poikilitic relations to quartz and feldpsar and also as discrete shreds, grains, and crystals. The poikilitic crystals show a network of the amphibole in optical continuity, with the interstices filled with grains or crystals of feldspar and quartz. The sponges range up to 3 millimeters in diameter, and all facies contain them. A gradation exists from crystals with relatively little riebeckite to those which are nearly massive with only minor amounts of included minerals. The riebeckite is strongly pleochroic in deep blue and yellowish green shades and has low birefringence, with an extinction angle of 5 to 7 degrees.

Most of the rocks contain small amounts of aegirite, aegirite-augite, or arfvedsonite in addition to the riebeckite. Aegirite-augite is most abundant in the marginal facies, especially at Agua Fria and Adobe Walls Mountain. It is present as phenocrysts or smaller grains, both of an early period of crystallization. Probably the concentration of the mineral is the result of a chilling of the border material with the development of a more basic selvage.

[1] Osann described this structure in the paisanite from the type locality.

TABLE 5.—*Modes of paisanitic riebeckite soda rhyolites*

(Volume percentages)

	1	2	3*	4	5*	6*	7	8	9
Quartz	22.7	20.2	19.2	18.1	16.8	17.8	12.6	91.6	11.2
Alkali feldspar	.....	.....	.....	.....	76.0	76.6	77.6		.....
Sanidine	.....	.....	.....	.....	.....	.....	.....	+	.....
Anorthoclase	67.9	69.3	72.9	66.4	.....	.....	.....	.....	76.8
Riebeckite	9.4	10.5	7.9	15.1	7.2	5.6	9.8	8.4	12.0
Aegirite	tr.	.....	tr.	0.4	+	tr.	.....	.....	.....
Arfvedsonite	.....	.....	.....	.....	tr.	.....	.....	.....	.....
Fluorite	.....	.....	.....	.....	+	.....	+	.....	.....
Calcite	tr.	.....	.....	.....	.....	.....	.....	.....	.....

1. Hen Egg Mountain.
2. Hen Egg Mountain.
3. Mountain 4500.
4. Mountain 4500.
5. Mountain 4638.
6. Sill east of Mountain 4500.
7. Mountain 4302.
8. Sill east of Hen Egg Mountain.
9. North part of Adobe Walls Mountain.

* = Analyzed specimen.

TRACHYTE

Trachytic rocks completely free of quartz have not been found in the region. A number of rocks, however, contain from a trace to a few per cent of the mineral and are in sufficient contrast to the rhyolites to warrant their classification as trachyte (No. VII, Table 17).

The analyzed specimen of trachyte is from one of two dikes cutting the soda trachyte three-fourths of a mile south of B. M. 3049. The rock is weathered to some extent with brownish and reddish surfaces, but freshest material is white aphanitic with a few glistening faces of feldspar. Microscopically the rocks consist of a trachytic groundmass of feldspar laths averaging 0.15 millimeter long in which are elongate lath-shaped microphenocrysts of feldspar with nearly square cross sections approximately 0.15 millimeter across. The microphenocrysts are anorthoclase ($2V = 55° \pm$; extinction $= 12°$ on 010, and $\gamma = 1.529$) with Carlsbad twins but in some cases with an obscure grid-iron twinning. The groundmass feldspar is soda orthoclase (?) (extinction $= 0°$ on 001, and $\gamma = 1.527$). Irregular yellow aggregates of epidote are secondary after a mafic mineral. Rare grains of limonite are scattered through sections. Minute vesicular cavities in the rock are filled with yellowish-gray opal sometimes slightly birefringent, and there is present interstitially another isotropic mineral of higher index of refraction than the opal tentatively identified as noselite. It is grayish to bluish gray and has an index of refraction of $1.48\pm$. The presence of a notable amount of SO_3 in this rock is thought to be due to the noselite (?). Microscopic examination failed to reveal a sulphide mineral, and Dr. R. B. Ellestad, the analyst, stated that the sulphur was present as sulphate and not sulphide.

Other trachytes with notable amounts of epidote and of the isotropic mineral are found at the small isolated sill 1 mile north of Study Butte and as a small pluglike mass intruding the soda trachyte directly west of Bee Mountain. In the former the rock is distinctly porphyritic with feldspar phenocrysts (anorthoclase, negative, 2V medium; extinction $= 10°$ on 010) reaching 5 millimeters in length; the groundmass is much coarser with feldspar laths averaging 0.4 millimeter. The isotropic mineral is largely interstitial.

Small dikes of light grayish-green trachyte cut the main mass of Indian Head Mountain. At the west flank of the mountain opposite Study Butte a porphyritic dike of trachyte has soda orthoclase phenocrysts up to 4 millimeters long. The groundmass is of alkali feldspar laths 0.25 millimeter long with subtrachytic texture. There are a few scattered grains of epidote and a trace of interstitial quartz. A small dike a few hundred yards north of the northwest corner of Indian Head

Mountain is a generally similar trachyte but with phenocrysts of sanidine.

In the Solitario trachytic rocks are generally oligoclase-bearing and correspond in this respect to the plagioclase-bearing rhyolites. The few

TABLE 6.—*Modes of trachyte*

(Volume percentages)

	1*	2	3
Quartz	2.0	2.0	1.1
Alkali feldspar	.....	88.0	92.9
Anorthoclase	+P	+P	.....
Soda orthoclase	86.0	.....	+
Epidote	6.0	7.0	4.0
Opal	3.0	.....	.....
Limonite	+	+	2.0
Noselite (?)	3.0	3.0	.....

P = Phenocrysts, included in total of other feldspar.
* = Analyzed specimen.
+ = Trace.

1. Half a mile south of B. M. 3049.
2. 1 mile north of Study Butte.
3. West of Bee Mountain.

examples found are porphyritic and occur in some of the thicker sills and dikes, in, along the borders of, or near the vent area. Two of the masses cut the vent agglomerate. The freshest material is found in a wall-like dike 100 feet thick exposed for nearly half a mile in the vent area three-fourths of a mile northeast of Mountain 4618. The rock is porphyritic with a cream-colored aphanitic matrix with many cream-colored feldspar phenocrysts up to 5 by 3 millimeters. The groundmass is trachytic with orthoclase laths averaging 0.2 by 0.07 millimeter. The phenocrysts include perthitic intergrowths of orthoclase and albite-oligoclase, armored grains of andesine (An_{36}), and a few discrete albite-oligoclase twins. Abundant secondary chlorite suggests biotite, and irregular areas of limonite appear likewise to be from original mafic constituents. There are a few grains of zircon, secondary calcite, and secondary quartz, the quartz and calcite sometimes being associated in vugs or areas occupied originally by mafic minerals.

SODA TRACHYTE

Soda trachyte is abundant in the eastern area and is present in three localities in the Solitario. Quartz-free representatives are not found,

but there is a sharp break in this respect between the soda trachytes and soda rhyolites. Variation is caused by differences in feldspar, mafic minerals, and texture. Anorthoclase is less abundant, and mafic minerals generally are more prominent than in the soda rhyolites.

One mile southwest of Mountain 4320, in the northeastern part of the area (Pl. 2), is a large mass of a soda trachyte (No. X, Table 17) with aegirite and arfvedsonite as the mafic minerals. The north flank of the mass is a cliff several hundred feet high flanked by great accumulations of debris. The surface is irregular with minor peaks and eminences, but there is no direct evidence to indicate that this mass is a lava flow. No clear-cut contacts are found, but the general character of the mass suggests that it is a sill intruded into the soft Late Upper Cretaceous beds and subsequently eroded. Externally the rock resembles the riebeckite rhyolite of Agua Fria Mountain and other localities. It is light greenish gray, aphanitic to fine-grained, with numerous dark specks of mafic mineral and rare phenocrysts of glassy lath-shaped feldspars up to 1 centimeter long, sometimes showing Carlsbad twins in the hand specimens. The rock varies somewhat from place to place but commonly has a trachytic texture in which the feldspar laths average 0.3 millimeter long. The texture becomes trachytoid in specimens in which part of the feldspar has a quadratic habit.

All the feldspar is alkali feldspar, and most of it is soda orthoclase (extinction $= 0°$ on 001 and $7°$ to $10°$ on 010; $\gamma = 1.527$). Much of it is present as slender Carlsbad twins, and the rare phenocrysts are of this same character and apparently of the same composition as the groundmass laths. In some specimens the feldspar includes clear stubby plates which apparently are similar optically to the laths. The mafic minerals include aegirite, arfvedsonite, and riebeckite, but the latter is subordinate in most specimens. Aegirite forms irregular prismatic grains with bright-green and yellowish-green pleochroism and an extinction angle of $6°$ to $8°$. Arfvedsonite occurs in prismatic to ragged grains with pleochroic colors of green, greenish blue, and brown. Its extinction angle is $18°$. Some specimens show rare spongelike crystals of riebeckite. All the mafic minerals are ophitic to feldspar and show a slight tendency toward the sponge type of crystal. In some specimens quartz is present in very small amounts as an interstitial material; in some, secondary calcite is developed.

A closely related but more mafic aegirite-riebeckite trachyte is found in the mountain immediately north of Mountain 4320. The rock is dark grayish green, aphanitic to very fine-grained. It consists of a trachytoid groundmass of clear soda orthoclase laths, rare microphenocrysts of anorthoclase (2V moderate; fine gridiron twinning), and fairly abundant

TABLE 7.—*Modes of soda trachytes*

(Volume percentages)

	1*	2	3	4	5	6*	7	8	9	10	11	12	13	14
Quartz	tr.	tr.	0.2	0.2	0.2	0.9	0.3	0.3	1.2	2.3	1.3	0.5	0.9	0.6
Alkali feldspar	.....	.....	.....	71.3	.....	.....	.....	.....	90.2	.....	.....	.....	.....	.....
Orthoclase	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	84.4	83.5	.....	.....
Soda orthoclase	80.2	82.6	72.2	.....	79.1	81.7	76.3	84.5	.....	85.9	.....	.....	88.9	78.8
Anorthoclase	.....	.....	+P	.....	.....	.....	+P	.....	.....	.....	+P	.....	+P	+P
Sanidine	.....	.....	.....	+P	10.0	.....	.....	.....	.....	+P	.....	.....	.....	.....
Albite-oligoclase	.....	.....	+P			.....	.....	.....	.....	.....	.....	.....	+P	.....
Augite	.....	.....	.....	.....	+P	.....	.....	.....	.....	.....	+	.....	.....	.....
Aegirite		17.4	.....		4.0	10.4	20.4	.....	2.6	11.8	1.0	16.0	.....	.....
Aegirite-augite	19.8		27.6W	28.5		.....	.....	15.2	.....	.....	12.3	.....	9.2	20.6
Riebeckite	+	+		+	.....	+	3.0	.....	6.0	.....	.....	+	+	+
Arfvedsonite	+	.....	.....	.....	6.7	7.0	.....	.....	.....	.....	+	.....	1.0	+
Iron ore	+	+	.....	+	+	.....	.....	.....	.....	.....	1.0	.....	+	+
Apatite	.....	+	+	.....	.....	.....	.....	.....	.....	.....	+	.....	.....	.....
Fluorite	.....	.....	+	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Calcite	.....	.....	+	+	.....	+	.....	.....	.....	+	.....	.....	.....	.....
Epidote	.....	.....	.....	+	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

P = Phenocrysts, amount included with other feldspar or other pyroxene.
W = Weathered to iron oxide.
* = Analyzed specimen.

1. Mountain 3513 northwest of Payne's Waterhole.
2. Hill between Mountain 3513 and Mountain 3049.
3. Round mountain immediately south of Mountain 3518.
4. Dike at north flank of Bee Mountain.
5. Small sill west of Wildhorse Mountain.
6. Large sill-like mass 1 mile southwest of Mountain 4320.
7. Rounded mountain north of Mountain 4320.
8. Dike 1¼ miles north of Bee Mountain.
9. West end of mountain 1 mile south of Mountain 4320.
10. Sill 1 mile northeast of Mountain 3505.
11. Bee Mountain.
12. Payne's Waterhole anticline.
13. Northwest flank Indian Head Mountain.
14. North flank Indian Head Mountain.

prismatic grains of aegirite and plates of riebeckite. There is a little interstitial quartz.

A soda trachyte in which aegirite-augite is the dominant mafic mineral is the principal rock type in Indian Head Mountain. The mass is one of the uncovered laccolithic intrusions in Late Upper Cretaceous beds. The rock is dark gray in most specimens with the freshest ones showing a greenish tint; it is distinctly porphyritic with abundant feldspar phenocrysts, mainly glomerocrysts averaging 3 by 4 millimeters. The groundmass is trachytic with lath-shaped Carlsbad twins averaging 0.4 by 0.1 millimeter with a minor number of irregularly equidimensional feldspar grains averaging 0.2 by 0.2 millimeter. Mafic constituents are generally interleaved with the groundmass feldspar, but there are a very few pyroxene microphenocrysts up to 0.4 by 1.5 millimeters. The feldspar phenocrysts are unusually fine anorthoclase ($2V = 50° \pm$; extinction $= 10°$ on 010) with distinct gridiron twinning. The phenocrysts enclose grains and crystals of the mafic minerals, sometimes roughly zoned along peripheral boundaries of the feldspar. The Carlsbad twins of the groundmass are soda orthoclase with extinction of 9° on 010. The irregular feldspar grains of the groundmass are tentatively identified as anorthoclase. The most prominent mafic mineral is aegirite-augite ($X \wedge c = 36°$) pleochroic in green, yellowish green, and grayish green. Microphenocrysts of the mineral are euhedral, but groundmass grains are irregularly prismatic. In addition to the pyroxene minor amounts of brown arfvedsonite ($X \wedge c = 15°$) and possibly riebeckite are present in irregular flakes and plates. Iron ore is a fairly abundant accessory, and there is a very little interstitial quartz. In some sections amphibole is proxied by a reddish-brown mineral, apparently iddingsite. Specimens from the northwest flank of the mountain are slightly coarser than those already mentioned and contain albite (positive, untwinned; extinction $= 16°$ on 010, n slightly lower than Canada Balsam) in addition to anorthoclase among the phenocryst feldspars. In this specimen also pyroxene and amphibole are intergrown, with pyroxene frequently mantling the amphibole.

A soda trachyte with considerable quartz, sanidine phenocrysts, and mafic constituents restricted to aegirite is found 1 mile northeast of Mountain 3505. The rock is greenish gray with a felty groundmass in which are minute black grains of mafic minerals and numerous lath-shaped feldspar phenocrysts up to 7 millimeters long. The groundmass has a good trachytic texture in which dusty Carlsbad-twinned laths of soda orthoclase (extinction $= 10°$ on 010) average 0.45 by 0.04 millimeter. The phenocrysts likewise are lath-shaped Carlsbad twins and are oriented in the trachytic texture. They are sanidine (2V small;

extinction = 0° on 001 and 6° on 010) and average 3 by 0.3 millimeter. The aegirite generally is interleaved with the groundmass laths and is bright green with a small extinction angle. It is partly altered to limonite, and some of this material may represent still another mafic constituent. There is a trace of calcite and a notable amount of interstitial quartz. A section from another collection, marked the same locality, is less porphyritic and contains brown arfvedsonite as the only mafic constituent.

The intrusive of Bee Mountain is a soda trachyte containing sufficient quartz to place the rock on the border line between rhyolite and trachyte. It is characterized by glomerocrysts of feldspar 4 by 4 millimeters composed of very good crystals of anorthoclase. The groundmass is trachytic with Carlsbad-twinned laths of orthoclase up to 0.4 millimeter long, a little interstitial quartz, and abundant mafic constituents. The anorthoclase phenocrysts (2V moderate; extinction = 10° on 010) show fine gridiron twinning and also Mannebach twins. They enclose grains of the mafic minerals. The mafic constituents include gray-green augite ($Z \wedge c = 55°$) frequently rimmed with green aegirite-augite, discrete grains of green aegirite-augite, rare grains of aegirite, and flakes and prismatic grains of brown arfvedsonite ($X \wedge c = 16°$). The latter frequently surround the pyroxene, suggesting reaction. Rare grains show augite centers surrounded by aegirite-augite and finally by the amphibole. The largest pyroxene grains reach 0.6 millimeter and range downward to minute grains. Iron-ore grains up to 0.16 millimeter are included in or border all the mafic minerals. An orange-yellow fibrous alteration product (iddingsite?) in the sections proxies augite. Minute apatite prisms also are present.

A border facies of this rock is strikingly different mineralogically. The rock is porphyritic with a dark greenish-gray aphanitic groundmass in which are abundant light chalky phenocrysts of feldspar up to 3 millimeters long. More prominent are irregular amygdular fillings of a glassy mineral with a bluish cast. Under the microscope the rock shows a dense felsitic groundmass in which minute laths of alkali feldspar, often spherulitic, are discernible. The groundmass is crowded with prismatic to needle-shaped crystals of aegirite. There are a few microphenocrysts of aegirite-augite and numerous phenocrysts of soda orthoclase. Amygdules are filled with a colorless mineral ($\alpha = 1.5309$ and $\gamma = 1.534$) with anomalous brown interference colors. This mineral replaces the feldspar and in some amygdules is accompanied by calcite.

The soda trachyte of Mountain 3513 (No. VIII, Table 17) is coarser than most examples and perhaps should be called soda microsyenite. Furthermore it contains more aegirite-augite than do most specimens.

The occurrence is probably an uncovered sill and rests on a nearly horizontal floor of Late Upper Cretaceous beds. The mass has been cut by a narrow dike of analcite trachybasalt porphyry. The rock is greenish gray, and under a lens the aegirite-augite shows as very abundant green grains. The texture is subtrachytic with a seriate range in feldspar laths, ranging in length from 1.5 millimeters to minute. A few phenocrysts of aegirite-augite are slender prisms 3 millimeters long, but most of the mineral is present as spongelike crystals poikilitic to feldspar and prisms averaging 0.4 millimeter long. There is a trace of riebeckite with sponge habit flakes of arfvedsonite, and anhedral iron-ore grains up to 0.15 millimeter across. The feldspar is lath-shaped soda orthoclase (2V large; extinction = 0° on 001 and 10° on 010) with many Carlsbad twins. The aegirite-augite ($X \wedge c = 34°$) is a deep green and is only slightly pleochroic.

The soda trachyte from the round mountain immediately south of Mountain 3518 is distinguished by the presence of a small amount of plagioclase (albite-oligoclase). The rock is fine-grained to aphanitic with rare glistening phenocrysts of feldspar up to 2 millimeters in length. The texture is trachytic with clear-cut laths of feldspar averaging 0.4 by 0.08 millimeter. The feldspar phenocrysts include discrete stubby laths and Mannebach twins up to 2 by 0.6 millimeter. Many of the larger phenocrysts are anorthoclase with well-developed fine gridiron twinning. A few stubby laths among the phenocrysts are albite-oligoclase with a mean index of refraction only slightly less than Canada Balsam and fine albite twinning. Rarely these are armored with potash feldspar. The groundmass feldspar laths are soda orthoclase (extinction = 0° on 001 and 10° on 010) in good Carlsbad twins. The mafic minerals are partly weathered and consist of prismatic grains and flakes of greenish pleochroic aegirite-augite and riebeckite. Probably the latter predominates, but because of the weathering this cannot be determined exactly. The mafic minerals show approximately the same grain size as the feldspar laths of the groundmass. Rare minute needles of apatite and interstitial fluorite also are present. Calcite has developed as a secondary mineral. There is a trace of interstitial quartz.

A small interrupted dike immediately north of Bee Mountain is aegirite-augite soda trachyte of distinctive texture. The rock is porphyritic with an aphanitic dark-green vesicular groundmass in which are numerous phenocrysts of sanidine (2V moderate to small; extinction = 0° on 001 and 5° on 010) 2 by 0.5 millimeter or larger, with Carlsbad twinning. Sometimes they are grouped into glomerocrysts. The groundmass consists of laths of alkali feldspar averaging 0.15 millimeter long, many of which are grouped in stellate arrangement. The "stars" consist of 5 to 10 feld-

spar laths radiating from a center, and in many specimens adjacent laths are separated by a ragged prismatic grain of aegirite-augite. The mafic constituents include a little riebeckite and iron ores, with traces of epidote, calcite, and interstitial quartz.

Two irregular disconnected outcrops of a sill 20 feet thick just west of Wildhorse Mountain are composed of a soda trachyte containing augite along with sodic pyroxene and minor amounts of albite. The rock is greenish gray with brownish grains and irregular areas from decomposed mafic minerals. Glassy feldspar phenocrysts up to 3 millimeters long are scattered through the fine-grained to aphanitic groundmass. The groundmass consists mainly of irregular lath-shaped Carlsbad twins up to 0.4 millimeter and irregularly quadratic grains of soda orthoclase averaging 0.3 by 0.4 millimeter. The laths do not show a common orientation, and interleaved with them are plates and prismatic grains of sodic pyroxene and amphibole ranging in size from minute to nearly the size of the feldspars. There is a little interstitial quartz. The phenocrysts include feldspar and microphenocrysts of pyroxene. The feldspar consists of Carlsbad twins of soda sanidine (2V small; extinction $= 9°$ on 010) and untwinned albite (extinction $= 13°$ on 010). Both are present in glomerocrysts of three or four individuals as well as in individual crystals. The pyroxene microphenocrysts are greenish-gray augite ($Z \wedge c = 47°$) up to 0.8 millimeter in length. Some of the augite shows narrow aegiritic borders. The augite crystals grade downward in size to similar pyroxene in the groundmass. Rarely the augite is enclosed in feldspar phenocrysts. Groundmass pyroxene also includes minute prismatic grains of bright-green aegirite. In addition to the groundmass pyroxene there is abundant arfvedsonite ($X \wedge c = 15°$) pleochroic in green, blue-gray, and brown. The mineral is the most abundant mafic constituent of the rock. Minute iron-ore grains are rather abundant.

A rather typical soda trachyte is present at Solitario Peak where a conical mass of the rock 300 yards in diameter has cut through rhyolite and the Lower Cretaceous sediments. The rock is medium to dark gray with many minute specks of mafic minerals. Under the microscope the rock is microporphyritic with laths and tablets of feldspar ranging from 1 by 0.2 millimeter to 0.6 by 0.5 millimeter in a mortarlike matrix of alkali feldspar elements averaging 0.1 millimeter. The mafic minerals range in size between those of the two generations of feldspar and frequently are interstitial between feldspar microphenocrysts. There is a small but indeterminate amount of interstitial quartz.

The feldspar microphenocrysts are soda orthoclase (extinction $= 0°$ on 001 and $11°$ on 010, and $\alpha = 1.525$, $\gamma = 1.529$) in Carlsbad twins and

untwinned crystals. Rarely the twinning is of cruciform type. The most prominent mafic mineral is brown strongly pleochroic arfvedsonite ($X \wedge c = 16°$). Greenish-gray aegirite-augite ($X \wedge c = 33°$), often rimmed with still more sodic pyroxene, also is present in notable amounts. Frequently the amphibole and pyroxene occur in a common aggregate suggesting reaction. Grains of iron ore are present generally in association with the amphibole and pyroxene.

Another soda trachyte in the Solitario with smaller amounts of soda-bearing mafic constituents and with some oligoclase-andesine is found as a dike at the western flank of the analcitic syenite mass in the central part of the Solitario. The rock is brownish with aphanitic groundmass in which are numerous biotite phenocrysts up to 3 millimeters long and rare flesh-colored feldspars up to 1 by 4 millimeters. Under the microscope the feldspars show a seriate range from the smallest grains of the groundmass to the largest phenocrysts. The phenocrysts include anorthoclase (2V medium; extinction = 7° to 10° on 010) with Mannebach and fine gridiron twinning, zoned plagioclase (An_{30} to An_{24}) armored with anorthoclase, and intergrowths of oligoclase and anorthoclase. The last feldspar to crystallize was lath-shaped Carlsbad twins of orthoclase averaging 0.15 by 0.03 millimeter. The mafic minerals include greenish-gray augite sometimes rimmed with aegirite-augite or even aegirite in prismatic grains and shreds 0.08 millimeter long, biotite showing all stages of resorption to magnitite, brownish soda-rich amphibole ($Z \wedge c = 22°$), and iron-ore grains up to 0.25 millimeter. Apatite is present in dusty prisms 0.25 by 0.08 millimeter, and there is some secondary calcite. It is possible that this rock is more closely related to the syenodiorite at the margin of the analcite syenite and to the syenodiorite porphyry from the east side of the vent area than to the soda trachyte of Solitario Peak. Dusty fat prisms of apatite are present in all except the rock from Solitario Peak.

TRACHYANDESITE-SYENODIORITE

Rocks classified in the group trachyandesite-syenodiorite are more diverse and probably are less closely interrelated than those of the other groups. They all contain potash feldspar and plagioclase, but the latter has a considerable range in composition. In many the plagioclase and orthoclase are nearly equal in amount. The prominent mafic minerals include amphiboles, pyroxenes, and biotite, but strongly sodic varieties are not important. A few representatives contain olivine.

A number of sills and dikes in the north and east-central part of the area (Pl. 2) are weathered, mainly buff-colored, fine-grained rocks of trachyandesitic composition. The greatest development of these rocks

TABLE 8.—*Modes of trachyandesite and syenodiorite*
(Volume percentages)

	1	2	3*	4	5	6	7
Quartz	.....	+	.....	.....	.....	.....	.....
Plagioclase	52.5	45.3	46.7	44.4	42.5	40.0	50.6
Kind of plagioclase	An 52–An 40	An 54–An 24	An 32–An 9	An 52–An 40	An 42–An 18	An 40–An 10	An 45
Orthoclase	.....	.....	45.0	.....	40.0	.....	20.0
Anorthoclase	.....	40.0	.....	.....	.....	36.1	.....
Alkali feldspar	40.0	.....	.....	40.0	.....	.....	.....
Hornblende	4.9	+	.....	14.5A	.....	.....	.....
Aegirite-augite	.....	+	.....	.....	.....	.....	.....
Augite	+	10.0	5.1	.....	10.6	9.0	21.3D
Biotite	.....	+	0.5	+	2.0	+	1.6
Iron ore	+	4.7	2.7	.....	3.9	3.0	2.6
Olivine	.....	+	.....	.....	1.0S	5.8S	.....
Apatite	+	+	+	+	+	+	.....
Titanite	.....	.....	+	.....	.....	.....	.....
Serpentine	.....	.....	+	.....	.....	.....	.....
Calcite	2.6	.....	+	1.1	.....	6.1	3.9
Analcite (?)	.....	.....	.....	.....	.....	.....	+

A = Altered to iron oxide.
S = Serpentinized.
D = Includes small amount of diopsidic pyroxene.
* = Analyzed specimen.

1. Hornblende trachyandesite, California Mountain.
2. Augite syenodiorite from wax factory laccolith.
3. Syenodiorite porphyry, southeast flank vent area of Solitario.
4. Trachyandesite, dike 1 mile south of Payne's Waterhole.
5. Microsyenodiorite, marginal facies of analcite syenite, Solitario.
6. Microsyenodiorite, anticline at Payne's Waterhole.
7. Trachyandesite, 1 mile west of Willow Mountain.

is on the flanks of the anticlinal structure near Adobe Walls. To the north of the structure several small mesas, remnants of an uncovered sill which had a gentle dip to the north, are capped by the rock, which has a thickness of 25 feet. On the immediate north and east flanks of the structure are thin sills 8 feet thick dipping steeply away from the structure. Southeast of the structure on the east side of the highway a sill 50 feet thick dips 34 degrees away from the structure. This sill is cut by a dike of analcite trachybasalt porphyry. Dikes and sills of somewhat similar rock are found just west of Terlingua Creek at the Reed Ranch, three-fourths of a mile southwest of Mountain 3518, and southeast of Sawmill Mountain. At the Reed Ranch locality a dike 30 feet thick stands vertically in Upper Cretaceous beds. The dike is composite containing pinkish to buff trachyandesite and black olivine basalt porphyry. The trachyandesite generally forms the walls of the dike and has been intruded by the basalt porphyry.

The trachyandesite from the sills on the flanks of the anticline near Adobe Walls is hornblende trachyandesite slightly porphyritic and with most of the hornblende altered to iron oxide. One or two giant hornblende phenocrysts 2.5 centimeters long were noted, but the hornblende ordinarily is present as minute dark grains. The original color of the rocks probably was grayish green, but most specimens are altered to buff or creamy gray. Microscopically the rocks consist of a matrix of feldspar laths and grains averaging 0.2 millimeter long, partly or completely altered prisms and needles of brown hornblende, grains of iron ore, rare dusty prisms of apatite, a little interstitial quartz, and considerable calcite, in which are sporadic phenocrysts of andesine (An_{48}) armored with alkali feldspar (anorthoclase ?). The groundmass feldspar includes alkali feldspar in discrete stubby grains and also as rims around plagioclase, and slender laths of medium oligoclase.

The smaller sills of trachyandesite are similar to that described, but the sill east of the highway southeast of the anticline has a microcrystalline, nearly glassy groundmass in which are slender laths of plagioclase. Brown acicular hornblende is prominent in this rock. The dike southeast of Mountain 3518 is composed of cream-colored trachyandesite with a few feldspar phenocrysts up to 2 millimeters long. The groundmass is trachytic and consists of laths of medium andesine averaging 0.3 millimeter long, quadratic grains of medium andesine armored with alkali feldspar (extinction = 11° on 010), abundant irregular small areas of iron oxide, and abundant needles of apatite. Sections contain one or two large flakes of biotite, but the abundant iron oxide was not derived from this mineral. The feldspar phenocrysts are sodic labradorite. Calcite is sparingly present as an alteration product.

1. Hornblende trachyandesite, California Mountain. 7. Trachyandesite, 1 mile west of Willow Mountain.

The igneous rock of California Mountain was described by Hill (1902, p. 25) as phonolite, but no specimens corresponding to his descriptions have been found. Considerable variation exists in the mass, however, and it is possible though unlikely that a phonolitic facies is present. The igneous mass is slightly elongate oval in plan and is pluglike or stocklike cutting Lower Cretaceous sedimentary rocks. Most of the rock is dark greenish gray, in some areas porphyritic with hornblende phenocrysts 1 by 5 millimeters. Another variation is medium gray with rare feldspar phenocrysts up to 3 millimeters long. Irregular dikelike and oval areas up to 40 feet in diameter of light-buff rock are present in the main mass of the rock. These appear to be normal rock which has been silicified by hydrothermal action. All specimens of the rock are somewhat altered with the development of calcite and other secondary products. The principal types are hornblende trachyandesite. In freshest specimens slender hornblende phenocrysts are common, but in others the mineral has been changed to iron oxide. The hornblende is green to yellowish green ($Z \wedge c = 23°$) in subhedral to euhedral crystals. Feldspar phenocrysts are not so abundant as hornblende and reach sizes of 1 by 0.7 millimeter. They are subhedral to anhedral, zoned from labradorite (An_{52}) to andesine (An_{40}), often with a very narrow rim of alkali feldspar. The groundmass feldspar consists of sharp laths 0.35 by 0.15 millimeter with albite twinning and minute irregular grains acting as a matrix for the laths. The laths are sodic labradorite zoned to andesine and like the rare phenocrysts, are armored. The smaller grains are alkali feldspar. There are very rare grains of gray augite and rather abundant grains of iron ore and stubby dusty prisms of apatite. Secondary calcite is abundant.

An analyzed syenodiorite porphyry from the southeast flank of the vent area in the Solitario (Pl. 1) is brownish green, phanerocrystalline with a fine-grained matrix and abundant dark reddish-brown phenocrysts of stubby lath-shaped feldspar averaging 3 by 4 millimeters with a few 7 millimeters long, and sporadic clots of augite up to 1 millimeter long. Under the microscope the rock shows a somewhat cloudy xenomorphic granular aggregate of feldspars and mafic minerals studded with clear euhedral to subhedral feldspar phenocrysts.

The feldspars of this rock are of considerable interest. The phenocrysts are of several types. Prominent are plagioclase with cores of andesine (An_{32}) zoned through oligoclase into albite with a narrow potash feldspar rim. Reaction in some cases carried the plagioclase only to oligoclase (An_{18}) before the armor of potash feldspar sealed off the core. There are also various types of perthitically intergrown feldspar, most common of which is an intergrowth of albite and orthoclase

found in the larger phenocrysts and also in the groundmass feldspar. There are present, also, intergrowths of oligoclase and orthoclase. In these a narrow outer rim of the latter mineral is present, often connected with the blebs of orthoclase in the oligoclase, which is the host mineral. Potash feldspar in all types of crystals is cloudy, and in some of the zoned crystals a narrow zone of cloudy material is surrounded by a narrow zone of clear feldspar, probably albite. The groundmass feldspar is present as stubby anhedral laths averaging 0.15 by 0.3 millimeter. Most of these are obscure intergrowths of orthoclase and albite, but some are armored grains of more calcic plagioclase. Mafic constituents are more abundant and generally are of the same size range as the groundmass feldspars with rare grains as large as the phenocrysts. They include gray augite ($Z \wedge c = 49°$) in subhedral grains, iron ore in discrete grains and as a reaction product, biotite of phenocryst size largely changed through reaction to iron-ore grains and feldspar, dusty stubby prisms of apatite, and rare minute grains of sphene. A little secondary calcite is present as well as serpentine apparently from biotite.

Rocks similar or at least closely related to this syenodiorite porphyry are found at other places around the borders of the vent area. At the west an irregularly oval mass of such rock intrudes the large rhyolite mass forming the west side of the vent area. The rock is a brownish trachyandesite porphyry with feldspar phenocrysts up to 1 by 1 centimeter. It has a groundmass of laths of orthoclase and nearly equidimensional grains of plagioclase armored with orthoclase. Other groundmass materials are augite, resorbed biotite, iron ore, and apatite. The phenocrysts include armored andesine (An_{32}) zoned to oligoclase (An_{24}), intergrowths of orthoclase and oligoclase, and oligoclase armored with orthoclase. The average of the plagioclase is near basic oligoclase or sodic andesine. There is a trace of interstitial quartz. Along the fault at the northeast boundary of the vent area another elongate mass of the rock is present, a porphyritic trachyandesite with phenocrysts up to 7 by 5 millimeters. The zoned plagioclase reaches andesine (An_{47}), and rare crystals of zircon were noted among the accessories.

The freshest rock on the crest of the Payne's Waterhole structure is brownish-gray, medium-grained augite-olivine syenodiorite porphyry with a very few lath-shaped feldspar phenocrysts up to 1 centimeter long. Weathered specimens are brownish through oxidation of the mafic constituents. Under the microscope the rock is a xenomorphic granular aggregate of feldspar with notable amounts of mafic constituents and secondary products. Most of the feldspar consists of anhedral roughly equidimensional grains with a central plagioclase core armored with anorthoclase. The feldspar phenocrysts include individuals similar to

the smaller grains of the groundmass and also perthitic intergrowths of oligoclase and alkali feldspar, probably anorthoclase ($\gamma = 1.529$). The armored grains frequently are zoned with inner cores as basic as andesine (An_{40}), surrounded by basic albite or oligoclase. In many grains there is no apparent zoning but simply a sharp break from andesine to the anorthoclase armor. In grains in which the anorthoclase armor is relatively wide the mineral shows minute gridiron twinning and moderate to small optic axial angle with $\gamma = 1.529$. The smaller feldspar grains include anorthoclase in discrete grains but similar to the armor of the plagioclase and also discrete grains of untwinned albite-oligoclase. These are only slightly below Canada Balsam in mean index of refraction and are optically positive. Olivine and augite are prominent mafic constituents in anhedral grains of the same size as the feldspars of the groundmass. The olivine is a peculiar grayish brown and shows distinct (010) cleavage. It has altered to green serpentine and magnetite. In some instances calcite has replaced the olivine, possibly without serpentine as an intermediate product. Augite is gray with $Z \wedge c = 45°$. Both the augite and olivine differ distinctly from these minerals as developed in the analcite-bearing rocks. Ilmenite with coatings and rims of leucoxene is present in subhedral grains only slightly smaller than the other mafic minerals. Apatite in slender prisms and grains is an inclusion in all other minerals, and there are a very few slender prismatic crystals of zircon and very rare flakes of biotite. Associated with calcite in interstitial and vuglike areas is greenish-gray opal with $n = 1.430$. A rather common association is calcite lining the walls of vugs and opal occupying the central area.

The syenodiorite outcrops in the most deeply eroded part of the anticline and is partly surrounded by soda trachyte (Pl. 2) and intermediate syenitic varieties. Contacts between the varieties appear to be gradational, and possibly the rocks are parts of one mass zoned through differentiation. A somewhat different soda trachyte outcrops separately at the extreme west end of the structure, and small dikes and sills of basaltic rock are present on the flanks of the structure. Their relation to the central igneous core of the mountain cannot be determined.

The laccolith near the abandoned wax factory on Fresno Creek (Pl. 1) is composed of a striking augite syenodiorite. The mass is about 150 feet thick and through erosion of its roof and dissection by the stream is well exposed. The margin is chilled to a fine-grained rock of basaltic appearance, and two similar dikes exposed in the bed of the creek may have been the feeders. The main mass of the rock is badly weathered to brownish material, but specimens from the creek are unchanged though colored a brilliant green from organic material. The main mass of the

rock is medium- to coarse-grained with rare larger feldspar plates 6 millimeters long. The texture is xenomorphic granular to monzonitic composed of feldspars, augite, aegirite-augite, hornblende, biotite, apatite, magnetite, and quartz. Sections show considerable mineralogical variation and some specimens approach syenite through decrease in amount of plagioclase. The feldspars average 1 by 1 millimeter and in the most abundant facies consist mainly of irregularly quadratic grains of plagioclase zoned from labradorite (An_{54}) to oligoclase (An_{24}) armored with anorthoclase (2V moderate; extinction = 2° on 001 and 11° on 010, fine gridiron twinning). A few grains are oligoclase without anorthoclase rims, and there are a few zoned grains without rims. Anorthoclase in discrete interstitial grains somewhat smaller than the bulk of the feldspar is also present. All the feldspars are poikilitic to the mafic minerals.

The most abundant mafic mineral is gray augite ($Z \wedge c = 47°$) in irregular prismatic grains up to 1 by 0.5 millimeter. Rarely the augite is rimmed with bright green aegirite-augite ($X \wedge c = 18°$) which is present also in a few discrete grains 0.1 millimeter long. Many grains of augite are associated with reddish-brown hornblende ($Z \wedge c = 25°$) in reaction relationships. Occasional clots composed of hornblende, iron ore, aegirite-augite, and feldspar suggest that reaction has completely changed augite. There also are discrete euhedral to subhedral crystals of the amphibole up to 0.4 by 0.15 millimeter. Iron ore is present in slender shreds 1 millimeter long and in euhedral grains 0.2 by 0.2 millimeter. Apatite forms needles up to 0.4 millimeter long and also stubby prisms 0.03 by 0.07. Rare flakes of deep reddish-brown biotite and very rare grains of olivine (?) are also present. There is a trace of interstitial quartz. Syenitic facies of this rock contain only a little plagioclase. Anorthoclase is abundant, there is little or no aegirite-augite, biotite is very rare, and mafic constituents generally are less abundant than in the other facies.

The marginal facies of the analcitic syenite mass of the Solitario is microsyenodiorite more mafic than those specimens already described. No sharp contact between the central syenite and the syenodiorite was observed, and in hand specimens the two rocks are similar. The rock is dark gray, heavy, fine-grained, with rare plates of feldspar up to 3 by 2 millimeters. Rare inclusions up to 3 centimeters in diameter appear to be from the dike to the west. Under the microscope the rock is markedly porphyritic with phenocrysts of feldspar, biotite, olivine, and a few iron-ore grains of phenocryst size. The groundmass is a xenomorphic granular to hypidiomorphic granular aggregate of feldspar, augite, biotite, and dusty apatite. The feldspar phenocrysts are (1) plagio-

clase zoned from medium andesine to basic oligoclase with an alkali feldspar armor, (2) basic oligoclase with albite twinning, and (3) perthitically intergrown oligoclase and orthoclase. Biotite phenocrysts range up to 1 by 0.3 millimeter and without exception show reaction with the formation of iron ore and feldspar. In many instances the reaction has been nearly complete, and aggregates of iron-ore grains are ghosts of the former biotite crystals. Olivine is proxied by serpentine and was sparingly present in subhedral crystals 1.2 by 0.4 millimeters. The groundmass feldspars, all of which appear to be alkali (mostly orthoclase), show a considerable range in size, including minute anhedral grains and laths with Carlsbad twinning. The groundmass includes a great number of prismatic grains of greenish-gray augite averaging 0.07 millimeter long. Iron-ore grains of the same size are somewhat less abundant, and both minerals form inclusions in the feldspar phenocrysts. A rather prominent accessory is apatite in minute needles and also in fat prisms up to 0.3 by 0.1 millimeter filled with minute dustlike inclusions.

A single example of an unusual trachyandesite is found in a small wall-like ridge standing above the Late Upper Cretaceous clay flat 1 mile west of Willow Mountain and north of Bee Mountain. It is about 400 feet long and nearly 100 feet wide and stands 40 feet above the general level. Its exact relations to the sedimentary rocks cannot be seen, but it evidently is dikelike or pluglike. The rock is grayish lavender, fine-grained to aphanitic with minute dark specks of mafic minerals, veinlets of pyrite, and blebs of calcite. It contains rounded to subangular inclusions of hornblende gabbro up to 3 inches in diameter, some of which suggest segregations rather than inclusions. The rock is roughly equigranular with laths of andesine (An_{45}) 0.15 millimeter long and anhedral grains of orthoclase 0.1 by 0.1 millimeter forming a matrix for abundant somewhat larger mafic minerals. The most prominent mafic constituent is light gray almost colorless augite ($Z \wedge c = 45°$) in prisms up to 0.35 millimeter long. A few greenish pyroxene crystals are 1.5 by 2 millimeters. These are zoned ($Z \wedge c = 32°$ to $38°$) and probably are diopsidic. Reddish-brown biotite flakes 0.1 millimeter across are rare but minute iron-ore grains are abundant. There are a very few microphenocrysts of andesine 0.7 by 0.5 millimeter, some of which are armored with orthoclase. Calcite is present in vugs and also is secondary after augite. There is a very small amount of isotropic material, possibly analcite.

The inclusions in the augite trachyandesite are mesotype hornblende gabbro. No other rock in the area even remotely resembles it. It is dark gray, equigranular, fine-grained, obviously rich in mafic con-

stituents which appear as dark cleavages between which is gray feldspar. The rock is composed of about 60 per cent labradorite and 40 per cent hornblende with traces of apatite and biotite. The hornblendes are generally subhedral averaging 1.2 by 0.6 millimeters, partly altered to chlorite, and completely peppered with minute grains of iron ore. The pleochroic shades are green, yellowish green, and brownish green. ($Z \wedge c = 15°$ and $\gamma = 1.685$; $\gamma - \alpha = 0.22$). The labradorite grains (An_{58}) averaging 0.6 by 0.4 millimeter are beautifully clear albite twins with rarely a little combined pericline twinning.

A porphyritic trachyandesite which contains minor amounts of sodic amphibole occurs in a sill southeast of Sawmill Mountain. The rock is yellowish green somewhat weathered, with an aphanitic vesicular groundmass with vesicles up to 3 millimeters in diameter and pinkish weathered stubby feldspar phenocrysts up to 8 millimeters long. A few phenocrysts are smaller slender laths. Altered biotite appears as hexagonal flakes and shreds up to 1 by 4 millimeters. The groundmass consists of a mat of minute slender soda orthoclase laths averaging 0.2 millimeter long, nearly rhomb-shaped crystals of anorthoclase 0.2 by 0.15 millimeter, and small grains of andesine armored with anorthoclase. In the interlath areas are very small slightly weathered prismatic grains of arfvedsonite and minute grains of iron ore. The feldspar phenocrysts include larger anorthoclase and smaller andesine crystals armored with anorthoclase. The biotite phenocrysts show an advanced stage of reaction to magnetite.

BASALT

Basaltic rocks without analcite are comparatively rare in the area. The known occurrences range from rather melanocratic olivine basalt or olivine basalt porphyry to picritic and lamprophyric types. Probably all of these contain more than normal amounts of potassium, and a few contain enough of this element, appearing in alkali feldspar, for the rock to be called trachybasalt. All these types are shown under the same symbol on the maps.

A small pluglike mass of basaltic rock 1 mile south of Mountain 3551 is relatively simple mineralogically. The rock is black aphanitic with rare glistening grains. It is microporphyritic with abundant microphenocrysts of labradorite (An_{60}) 1.2 millimeters long with good albite twinning, anhedral fresh olivine and iron ore up to 0.3 millimeter in a very fine matrix of labradorite laths, anhedral feldspar grains, augite, and iron-ore grains. The iron-ore grains and augite are intergrown in clumps or knots and are ophitic to the feldspar laths. Possibly some of the anhedral feldspar grains of the groundmass are alkali feldspar,

and some of the labradorite phenocrysts show a very narrow rim of the same material.

Near B. M. 2671 north of Terlingua on the Alpine road a dike 1½ feet thick and the cap of a small conical hill are composed of basalts.

TABLE 9.—*Modes of basaltic rocks*

(Volume percentages)

	1*	2*	3	4
Orthoclase	30.3	0.3	.....	.....
Plagioclase		12.0	38.6	40.6
Kind of plagioclase	An_{65}	An_{64}	An_{60}	.....
Glassy matrix	34.3	25.6	.....	.....
Augite	19.3	38.0	30.0	30.7
Olivine	10.9	21.0	5.5	13.9
Ores	5.2	3.1	25.9	14.8
Biotite	.....	+	.....	.....
Apatite	.....	+	.....	.....
Amphibole	.....	.....	.....	+

* = Analyzed specimen.

1. Lamprophyric basalt, near B. M. 2671 on Alpine road.
2. Picritic basalt, Mountain 3607.
3. Basalt, 1 mile south of Mountain 3551.
4. Olivine basalt porphyry, near B. M. 2671 on Alpine road.

The dike is an olivine basalt slightly porphyritic with perhaps sufficient alkali feldspar to justify its being called alkali basalt (No. XVIII, Table 17). In a groundmass of minute labradorite (An_{60}) laths, prisms of purple augite, and grains of iron ore there are larger laths and grains of labradorite 0.5 millimeter long and pseudomorphs of serpentine after olivine of about the same size. Many of the plagioclase grains have a narrow armor of alkali feldspar, and there is a small amount of fine nearly glassy material in the groundmass which probably is chemically identical. In the groundmass, also, is a trace of brown amphibole (?) in minute crystals. The basalt of the hilltop is somewhat porphyritic with phenocrysts of purple augite and olivine ranging from 2 millimeters long down to minute grains of the groundmass. In addition to augite and olivine the groundmass contains grains of iron ore, minute laths of labradorite (An_{65}), and a cryptocrystalline or glassy matrix. The rock has considerably more olivine and augite than the dike.

In the multiple dike near the Reed ranch porphyritic olivine basalt has cut trachyandesite. Labradorite phenocrysts (An_{62}) up to 3 millimeters long, serpentinized euhedral olivine, and augite 0.5 millimeter

long are set in a trachytic groundmass of plagioclase laths, augite, iron-ore grains, and interstitial cloudy, nearly isotropic material. Some of the plagioclase crystals are zoned to andesine (An_{44}). The interstitial cloudy material probably indicates the alkalic character of this rock.

Mountain 3607, an oval pluglike mass, is composed of basalt generally similar to that already described but so rich in augite and olivine and so poor in feldspar as to warrant the designation of picritic basalt (No. XX, Table 17). Fresh olivine and gray zoned augite ($Z \wedge c = 42°$ to $49°$) with a size range from 0.1 to 3 millimeters are the most abundant constituents of the rock. These along with grains of iron ore and prisms of apatite are held in a groundmass of minute labradorite laths (An_{64}), grains of alkali feldspar, and faintly polarizing brown turbid felsitic material. In the groundmass material there are a very few minute grains of analcite (?) and wisps of brown biotite.

The best example of olivine trachybasalt is a sill 40 feet thick 2¼ miles due east of Mountain 3513. The rock has a dark-gray fine-grained groundmass in which are phenocrysts of feldspar (labradorite An_{59}) and olivine up to 2 millimeters long. The matrix consists of laths of plagioclase, grains of alkali feldspar, slightly purple augite, olivine, and iron ore. Alkali feldspar is approximately one-fourth of all the feldspar of the rock.

ANALCITE ROCKS

GENERAL DESCRIPTION

Rocks containing analcite are very abundant in the region, especially in the east-central area in the lowest part of the dropped block (Pl. 2). They include many dikes 1 to 20 feet thick, numerous sills 2 to 200 feet thick, a few small pluglike oval masses, and a number of laccoliths up to three-fourths of a mile in diameter. Most of the rocks are medium to dark gray, and since many are fine-grained or porphyritic they are of basaltic aspect. A very few are light-colored, and a few are coarse-grained. The rocks constitute a series with very perfect gradation from syenitic types to melanocratic feldspar-poor varieties. Analcite ranges from traces to over 25 per cent but is partly post-magmatic in origin. Available chemical analyses of the rocks include Nos. XI, XIII, XIV, XV, XVI, XVII, XIX and XXI of Table 17.

ORIGIN OF ANALCITE

Many of the rocks contain more than 10 per cent of analcite, and some more than 25 per cent. All the analcite is of late formation, but evidence in the sections indicates that its period of formation extended from a very late magmatic stage into a period definitely post-magmatic. Its origin has a direct bearing on classification of the rocks.

The paragenesis of the mineral corresponds with some exceptions to the account given by Scott (1916) for the mineral in Scottish rocks. Likewise, textures and mineral relations described by Jahns (1938) for Colorado analcite-bearing intrusives could be duplicated in the Terlingua rocks. In general the smaller rock masses, dikes, and sills intruded beneath a thin cover contain the smallest amounts of the mineral, and the larger or deeper masses contain the largest proportions. In the later stages of crystallization all the magmas concerned possessed an analcite-rich residual fraction in the interstices between earlier formed crystals. At this stage final consolidation of many of the smaller masses occurred without much reaction between liquid and crystals and with an effect much like that of a laboratory "quenching experiment." Such rocks can be regarded as "quenched rocks" since they record the progress of the magmatic process as of a certain stage. In larger masses in which the cooling period was extended, extensive reaction between the residual liquid and earlier formed crystals took place, and a whole train of reaction products resulted. The earlier stages of this reaction probably can be regarded as late magmatic because the products of reaction include aegiritic rims on augite, reaction of mafic minerals to biotite, and the development of ocellar analcite. Later stages probably are definitely post-magmatic because they include such features as vesicles filled with analcite associated with calcite and zeolites and the obliteration of primary igneous textures. Associated with this post-magmatic stage is the development of euhedral analcite crystals in sedimentary rocks of the region such as described by Milton (1936).[2] Similarly a few examples have been found of acid obviously nonanalcitic igneous rocks which contain analcite in vesicles.

Many of the smaller "quenched" masses contain analcite only in wedge-shaped grains or areas between the other minerals (Pl. 7, fig. 1). Such a relationship suggests primary origin but also limits the period of formation to the very end of the crystallization period. Narrow dikes of analcite trachydolerite and analcitic trachybasalt porphyry between Wildhorse Mountain and Willow Mountain and 1 mile northeast of Mountain 3518, however, contain analcite in relations suggesting a slightly earlier period of formation. The dike northeast of Mountain 3518 is a porphyry with dark aphanitic groundmass and labradorite phenocrysts. It contains 3.6 per cent analcite, 35.4 labradorite, 34 orthoclase, 18.9 augite, 2.5 olivine, 5.6 of ores, and traces of zeolites and

[2] Correspondence with C. P. Ross indicates that the analcite shale described by Milton is from the same locality, Section 248, Block G4, northeast of Terlingua from which the author reported analcite (Lonsdale, 1928, p. 449-450). The rock was at that time erroneously called a basalt, but reexamination has confirmed Milton's report that it is a black foraminiferal shale.

FIGURE 1. BIOTITE-AUGITE GRANOPHYRE
Main mass of Wildhorse Mountain; crossed nicols. X40.

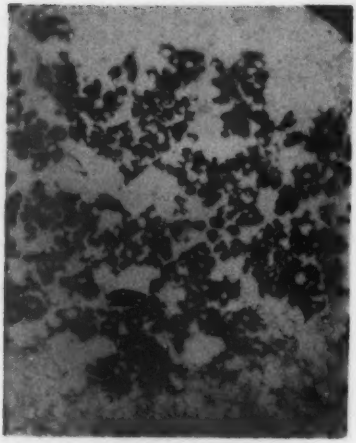

FIGURE 2. RIEBECKITE CRYSTAL
Spongelike poikilitic crystal from paisanitic riebeckite soda rhyolite, Hen Egg Mountain. X38.

FIGURE 3. REACTION NEST
Matted aggregate of analcite, chloritic material, biotite, sodic pyroxene, and alkali feldspar; from analcite plagioclase syenite, 1½ miles south of Mountain 4320. X220.

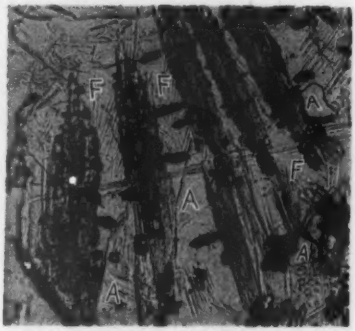

FIGURE 4. QUENCHED ROCK
Analcite (A) and alkali feldspar (F) between microlites of augite ophitic to labradorite in analcite trachybasalt porphyry, 1 mile northeast of Mountain 3518. X220.

TEXTURES AND PARAGENESIS OF ANALCITE

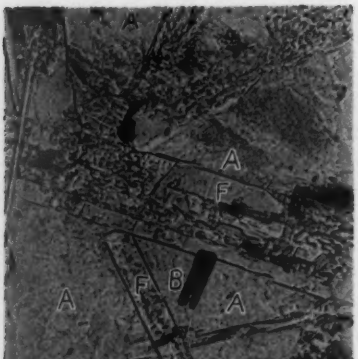

FIGURE 1. INTERSTITIAL ANALCITE
Analcite (A) interstitial to feldspar (F) and biotite (B) in analcite trachydolerite, 1 mile northeast of Mountain 3513. X252.

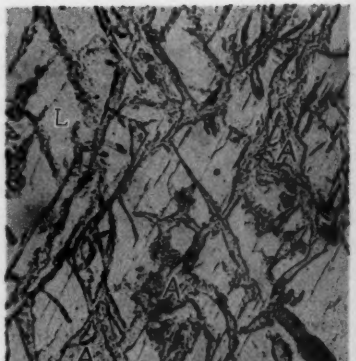

FIGURE 2. REPLACEMENT ANALCITE
Analcite (A) replacing labradorite (L) in analcite syenogabbro from Mountain 3000, 3 miles northeast of Terlingua. X118.

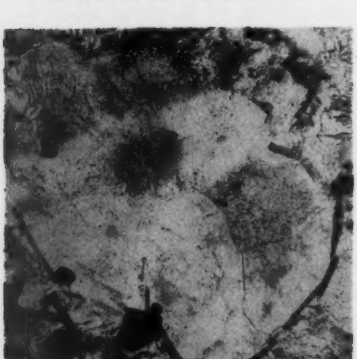

FIGURE 3. OCELLAR ANALCITE
Wisps of biotite tangential to analcite in analcite syenogabbro, 2 miles northeast of Mountain 3519. X56.

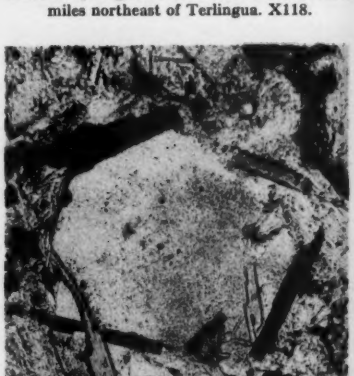

FIGURE 4. OCELLAR ANALCITE
Same locality as Figure 3 but smaller area of analcite nearly completely surrounded by the biotite. X130.

PARAGENESIS OF ANALCITE

calcite. The augite is present as microlites which are bundles of parallel or subparallel needles obviously the skeletons of augite crystals whose crystallization and growth were halted by the chilling of the dike. A few of the bundles are coalesced into solid crystals, and there is something of a gradation in this respect. If crystallization had been complete, the augites would have been ophitic to labradorite. The space between microlite rods is filled mainly with a mesostasis of alkali feldspar, but included are grains or wedges of clear analcite (Pl. 6, fig. 4). This relationship is believed to indicate that before the normal crystallization of augite was completed analcite liquid was present. It does not follow that analcite is contemporaneous with alkali feldspar, but it was formed not long afterward. Analcite of this sort is regarded with confidence as late magmatic. In this rock there are also a few vesicles filled with analcite and a few larger interstitial areas of turbid analcite which may have been formed still later, but the minute clear areas are magmatic. Reaction between the liquid and earlier crystals was limited in this rock. Plagioclase phenocrysts contain minute cracks filled with analcite, olivine crystals are serpentinized only at their borders, there is a slight development of chlorite (?) replacing alkali feldspar, and biotite is absent. The rock from the dike between Wildhorse Mountain and Willow Mountain differs only in that the olivine is completely serpentinized.

In the coarser rocks from the larger masses analcite generally is more abundant, and greater reaction has taken place, though in many such rocks much of the analcite is believed to be of late magmatic origin. The analcite syenogabbro from Cigar Mountain illustrates this condition. The rock contains 24 per cent analcite, 33.6 plagioclase, 20 alkali feldspar, 8.2 augite (including aegirite-augite), 4 olivine, 7.2 ores, 1 biotite, 0.2 apatite, and 1.8 zeolites. The plagioclase is replaced by analcite along cracks and cleavage lines, the amount of replacement varying up to one-fourth of the volume of individual crystals. Alkali feldspar, however, is not replaced by analcite. Analcite also is interstitial mineral enclosing other minerals. Magnetite and biotite tend to form clots generally near augite and olivine. Olivine is slightly changed to serpentine, and titaniferous augite has green aegiritic rims. A minor constituent not included in the mode consists of "reaction nests." These are irregularly distributed areas of material with a fuzzy appearance much finer than the rest of the rock. They are composed of weakly birefrigent material (probably feldspathic) in which are minute laths of alkali feldspar, grains of analcite, wisps of reddish-brown biotite, grains of green aegiritic pyroxene, and possibly brown amphibole. In

some areas zeolites are present. Olivine in contact with the "reaction nests" appears to be more altered than in other areas.

The "reaction nests" are present in a number of the coarser rocks and in some finer ones (Pl. 6, fig. 3). They are most common in the rock containing notable amounts of biotite. The "reaction nests" appear to represent a product of reaction late in the magmatic stage between residual liquid and earlier-formed constituents. A considerable part of the analcite of the coarser rocks is contemporaneous with these nests, and because of its association with biotite, aegiritic pyroxene, and alkali feldspar is thought to be magmatic. In some of the rocks this stage is marked by the development of ocelli (Pl. 7, figs. 3 and 4) of analcite bounded by biotite, but these are not present in the rock from Cigar Mountain.

The final analcitization phenomenon which is post-magmatic consists of additional reaction between the liquid and earlier solid products. Analcite replaces plagioclase until only ghostlike outlines of the crystals remain, alkali feldspar often is proxied by chloritic aggregates, olivine is completely serpentinized, biotite changes to chlorite, and frequently zeolites are formed. In extreme cases the original feldspathic minerals, olivine, and biotite may be more than half destroyed, but the pyroxenes are relatively unaffected. Albitization is not so important in these rocks as in the analcite rocks in Scotland (Scott, 1916), nor was it important in other American localities (Gilluly, 1927; Jahns, 1938) of analcite-bearing rocks. In the Terlingua area in a few of the plagioclase-rich types in which analcitization has been extensive, basic plagioclase shows minor albitization. The albite is nearly contemporaneous with late magmatic analcite.

The paragenesis of analcite in these rocks corresponds almost exactly to that described by Jahns (1938, p. 20-22) for the Colorado rocks. Formation of the mineral began during the magmatic stage and continued through a deuteric period into a stage marked by hydrothermal action. In some of the rocks weathering effects are superimposed on the results of earlier processes. The early and late stages in the formation of the mineral are plain, but the final stages of magmatic and deuteric action are not so evident. Much of the analcite especially in the more basic rocks was formed contemporaneously with or slightly later than typically magmatic reaction products such as biotite, sodic pyroxene, and alkali feldspar. Some analcite associated with zeolites and other late minerals unquestionably was of deuteric or hydrothermal origin. In all except the "quenched rocks" primary analcite cannot readily be separated from later analcite, but it seems certain that much of the mineral was primary.

CLASSIFICATION

Existing classifications of igneous rocks are not entirely satisfactory for the description and classification of these analcite-bearing rocks. Analcite was formed through a rather long period extending from late

TABLE 10.—*Classification of analcite-bearing rocks*

	Phanerites	Aphanites
Plagioclase<1/8 of feldspar.	Analcite syenite Analcite-nepheline syenite	Analcite trachyte (no example)
Plagioclase, andesine or labradorite, 1/8 to 4/8 of feldspar.	Analcite-plagioclase syenite Analcite-andesine syenite Analcite-labradorite syenite	Analcite latite (no example)
Alkali feldspar, 1/8 to 4/8 of feldspar, plagioclase averages andesine.	Analcite syenodiorite (no example)	Analcite trachyandesite
Alkali feldspar, 1/8 to 4/8 of feldspar, plagioclase averages labradorite.	Analcite syenogabbro Analcite trachydolerite	Analcite trachybasalt Analcite trachybasalt porphyry
Alkali feldspar<1/8 of feldspar. Plagioclase averages andesine. Plagioclase averages labradorite.	Analcite diorite (no example) Analcite gabbro Analcite diabasic gabbro	Analcite basalt Picritic analcite basalt

Analcitic = Analcite<5% of rock.
Analcite = Analcite>5% of rock.

magmatic into post-magmatic stages with extensive reaction and replacement of earlier-formed minerals, and it is obvious, in many of the rocks, that much of the analcite is post-magmatic. To use all the analcite as an important factor in classification gives an erroneous picture. As a group the rocks are composed essentially of variable proportions of alkali feldspar and basic andesine or labradorite along with augite, aegirite-augite, olivine, ores, and biotite, with variable amounts of analcite. A rock with equal amounts of alkali feldspar and labra-

dorite, considerable amounts of mafic minerals, and a few per cent of analcite under reaction may become rich in analcite and poor in plagioclase. From such an original rock a whole series of varieties might result, depending on the stage of reaction. The basis for a logical classification of these rocks is found in chilled facies and others in which extensive post-magmatic reaction has not occurred. In such rocks the analcite is largely interstitial, olivine is only partly serpentinized, and plagioclase is replaced only along cracks and cleavage lines (Pl. 7, fig. 2). If types determined on this basis are set up, it is possible to discern, at least dimly, their equivalents in the rocks extensively changed by post-magmatic analcitic reactions. The chilled rocks range from alkali feldspar-rich rocks with aegiritic augite or augite with aegiritic rims through rocks with notable amounts of both alkali feldspar and plagioclase and less aegiritic augite into rocks with predominant labradorite and purple augite. Any member of this series under extensive post-magmatic reaction undergoes changes in mineral composition and texture. The classification of the rock is best made by reconstructing its character before post-magmatic reaction and ignoring the extensive amounts of some of the reaction minerals. Fortunately not many of the rocks show extreme change and reaction; generally it is possible to secure a fairly definite picture of the original rock and relate it to the chilled types. The classification used is presented in Table 10. In general Niggli's (1931) divisions are followed, and the names used are chosen to emphasize the relation between alkali feldspar and plagioclase feldspar rather than the amount of analcite. The prefixes analcite and analcitic are used to indicate the importance of the mineral. Many of the rocks described as phanerites approach the lower limit of grain size for such rocks and are micro rocks.

ANALCITE SYENITE

Rocks classed as analcite syenite or equivalents are not abundant. The few examples found show a considerable mineralogical and textural range. One contains nepheline.

The analcite trachydolerite 1 mile northeast of Mountain 3513 is cut by stringers 2 inches thick of light-gray, medium-grained analcitic syenite. Hand specimens show abundant light-gray to white laths of feldspar, rounded areas of white zeolites, and minute grains of mafic minerals. The texture is hypidiomorphic granular with, however, a large proportion of the constituents euhedral to subhedral. Alkali feldspar, the most abundant constituent, forms prominent tablets averaging 2 by 0.6 millimeters, with nearly square cross section, and irregular anhedral grains. Many of the laths are clear and colorless, with Carlsbad twins. They show

extinction angles of 3° and 13°, an indistinct gridiron twinning, and a moderate optic axial angle, and probably are anorthoclase. Other laths enclose regular rectangular areas which are turbid and decomposed to white or gray opaque material. These turbid portions evidently are ghosts of another feldspar, probably oligoclase, since some of the anhedral grains of feldspar show incompletely the same type of alteration and are negative with large axial angle and indices of refraction close to that of balsam. Augite is subhedral to euhedral in slender prisms. The crystals are zoned with grayish-violet cores ($Z \wedge c = 48°$) and green aegiritic rims. Discrete small grains of aegirite with extinction angle of 4° also are present. Analcite is rare and is entirely interstitial. It is clear and limpid and shows faint double refraction. A number of interstitial areas appear similar to the alteration product of feldspar previously mentioned but cannot be identified as analcite. There are also a few small "reaction nests" consisting of a mat of chloritic material containing grains of aegirite and needles of alkali feldspar.

One igneous mass in the Solitario (No. XIII, Table 17) consists of analcitic microsyenite. The rock is dark gray and equigranular in hand specimens except for very rare larger feldspar plates up to 4 millimeters long. The feldspar includes both plagioclase and alkali feldspar, but the former is present in only small amounts. In rare larger laths it is andesine (An_{40}) with albite twinning, but these are zoned and also armored with alkali feldspar. Probably the bulk of the plagioclase is oligoclase (An_{24}), scattered uniformly through the sections and twinned only rarely. Occasional larger grains appear to be intergrowths of oligoclase with anorthoclase. Anorthoclase (2V moderate; extinction = 3° on 001 and 8° on 010, and $\alpha = 1.523\pm$, $\gamma = 1.529\pm$) probably is the most abundant alkali feldspar. Numerous sections show an indistinct fine gridiron twinning. The mineral is present in irregular grains, as armor on plagioclase, in intergrowths with oligoclase, and in a few laths with Carlsbad twins. Augite ($Z \wedge c = 44°$) is gray with a suggestion of violet. It is present in irregular anhedral grains some of which are slightly ophitic to the feldspar. Olivine ($\alpha = 1.659$, $\gamma = 1.693$) is more prominent than augite and is only slightly serpentinized. Rare anhedral grains are 0.5 millimeter in greatest dimension, but most grains are much smaller. There is a marked tendency for the mineral to associate with biotite and iron ore in clusters or knots suggesting a reaction relation. The latter minerals are largely restricted to this position. Apatite is present in fat prisms with dustlike inclusions. The very limited amount of analcite is surely primary. It forms rare interstitial grains and rare almost submicroscopic veinlets and specks in the feldspars.

The rock of the main mass of Mountain 3505 is a fine-grained porphyritic analcitic microsyenite resembling soda trachyte and identified as an analcitic rock only by microscopic examination. The rock is brownish gray somewhat weathered, with minute laths of feldspar roughly aligned,

TABLE 11.—*Modes of analcite syenite*
(Volume percentages)

	1	2*	3
Analcite	13.5	3.4	2.0
Plagioclase	5.2	10.0	.....
Kind of plagioclase	An_{52}	An_{40}–An_{24}	.....
Alkali feldspar	65.0	.....	80.8
Anorthoclase	.....	71.3	+P
Augite	9.1	2.6	15.2L
Aegirite-augite	+		
Aegirite	.....		
Olivine	2.8	2.6	.....
Ores	4.2	6.1	2.0
Biotite	+	4.0	.....
Apatite	0.2	+	.....
Calcite	+	.....	+

* = Analyzed specimen.
P = Phenocrysts included in total of other feldspar.
L = Partly altered to limonite.

1. Analcite microsyenite, three-fourths of a mile southeast of Mountain 3513.
2. Analcitic microsyenite, Solitario.
3. Analcitic microsyenite, Mountain 3505.

dark spots of mafic minerals, and feldspar phenocrysts up to 5 millimeters long. The groundmass is subtrachytic with bundles of laths of soda orthoclase 0.6 millimeter long with Carlsbad twinning interleaved with plates of bright-green aegirite partly altered to limonite. The phenocrysts of feldspar are anorthoclase (2V medium), some with fine gridiron twinning. Larger grains of mafic minerals include gray augite rimmed with aegirite-augite in euhedral to anhedral grains to 0.5 millimeter long and iron ore about the same size. Analcite is a sparse interstitial material, and calcite is secondary.

The main mass of Sawmill Mountain (No. XI, Table 17) is brownish, slightly vesicular analcitic microsyenite porphyry with a fine-grained groundmass in which are numerous lath-shaped and irregular feldspar phenocrysts up to 6 millimeters long. The groundmass is composed mainly of Carlsbad-twinned laths of orthoclase averaging about 0.4 millimeter

long, but with these are quadratic plates up to 0.3 by 0.4 millimeter of anorthoclase ($2V = 50° \pm$; extinction $= 12°$ on 010) with fine gridiron twinning. Mafic minerals are in the groundmass range of size. Most abundant is greenish-gray slightly pleochroic pyroxene in prismatic grains averaging 0.15 millimeter long with a few as large as 0.45 millimeter. The mineral is zoned in color and optically with centers of augite ($Z \wedge c = 49°$) and borders of aegiritic pyroxene. Iron-ore grains are present as inclusions in much of the pyroxene, and rarely a little biotite borders the pyroxene as a reaction product. The groundmass also includes rare irregular to subhedral areas of serpentine after olivine, fat prisms of apatite, and grains of iron ore. The feldspar phenocrysts are glomerocrysts of zoned and armored plagioclase. The zoning ranges from andesine (An_{48}) cores (positive, extinction $= 7°$ on 001 and $14°$ on 010) to outer zones of albite-oligoclase. Nearly every individual in the glomerocrysts has an outer rim of potash feldspar, probably anorthoclase. Rarely analcite replaces the feldspar and occurs as interstitial material. The border facies of this mass differs from the main mass in that plagioclase is less abundant, the pyroxene is aegerite-augite, olivine is absent, and analcite tends to occupy vesicles. In addition the texture is decidedly trachytic. The rock thus grades into the soda trachytic rocks.

ANALCITE-NEPHELINE SYENITE

Only one nepheline-bearing rock has been found in the region. It occurs as minor parts of a small sill-like mass 2 miles northeast of Mountain 3518. Here the major part of the mass is analcite syenogabbro, with irregular areas and stringers of a light-colored nepheline-bearing rock; the syenogabbro also encloses blocks of chalky limestone several feet in diameter. The rock is light gray, fine-grained, with a "pepper and salt" aspect due to dark grains of mafic mineral. Rare feldspar cleavages are 4 millimeters long, larger than the general grain size, but the rock is quite even-grained. Under the microscope the rock is a hypidiomorphic granular aggregate rich in alkali feldspar with a little plagioclase, abundant analcite, and nepheline with considerable amounts of aegirite-augite, augite, brown hornblende, biotite, and iron ores. The alkali feldspar consists of irregular tablets of soda orthoclase (2V large; extinction $= 10°$ on 010) irregularly intergrown with albite. These range from 2 by 0.5 millimeters down to minute laths. Carlsbad twinning is present in a few specimens. The alkali feldspar shows a slight amount of replacement by analcite, a condition not usually present in the analcite-bearing rocks. Andesine (An_{36}) armored with alkali feldspar is very rare with an average of one or two grains to a section. The nepheline is subhedral to euhedral in fresh colorless crystals up to 0.4 by 0.6 millimeter, and the

analcite is mainly interstitial with wedge-shaped areas of colorless material. Some hexagonal and tabular areas suggest original nepheline, but there are no examples of partial replacement of nepheline. The pyroxene also shows the soda-rich character of the rock. A few larger subhedral crystals 1.5 by 0.07 millimeters contain inner cores of grayish-violet augite ($Z \wedge c = 50°$) grading outward into bright green aegirite-augite with extinction angles of 29°. In addition to these crystals discrete smaller grains of the green aegirite-augite and possibly also minute grains of aegirite are present. Euhedral prismatic crystals of reddish-brown hornblende 0.6 by 0.15 millimeter and reddish-brown biotite in shreds and flakes of the same size are also present among the ferromagnesian minerals. Grains of iron ore and minute apatite crystals are rare.

ANALCITE-PLAGIOCLASE SYENITE

General statement.—In many analcite-bearing rocks alkali feldspar predominates over plagioclase, but the latter is plentiful. Accordingly, these rocks are classed as analcite-plagioclase syenite or their finer equivalents. To designate them simply as syenites fails to emphasize the fact that the rocks contain notable amounts of plagioclase, while to call them syenogabbros or syenodiorites would be erroneous since alkali feldspar predominates over plagioclase. Actually the rocks are very similar to syenogabbros and syenodiorites except for the different ratio between alkali and plagioclase feldspar. Depending on the type of plagioclase, analcite-andesine syenite or analcite-labradorite syenite can be distinguished. There is no marked difference between a rock with basic andesine and another with acid labradorite. A few contain plagioclase as sodic as An_{34}, while in others it is as calcic as An_{60}. The other minerals are those common to the analcite syenogabbros and syenodiorites—augite generally showing aegiritic rims, partially or wholly serpentinized olivine, variable amounts of analcite, and frequently several per cent of biotite.

Analcite-andesine syenite.—The analyzed specimen (No. XIV, Table 17) is an analcite-andesine microsyenite from an uncovered sill forming the top of a round mountain 1 mile southeast of B. M. 3049. The rock is fine-grained, medium gray, and appears equigranular to the unaided eye. A lens shows dark specks or grains of mafic minerals evenly distributed through gray feldspar cut by threadlike veinlets of zeolites. Under the microscope the rock is a hypidiomorphic granular aggregate which except for rare larger plagioclases has an average grain size, based on the abundant feldspar laths, of 0.5 by 0.15 millimeter. Rare plagioclase laths reach lengths of 3 millimeters, and iron-ore and

olivine grains average about 0.15 millimeter. The alkali feldspar consists of soda orthoclase (extinction = 11° on 010, and $\gamma = 1.528$) in clear sharp laths, some showing Carlsbad twins, and as armor on plagioclase. There are a few larger plagioclase laths with albite twinning,

TABLE 12.—*Modes of analcite-plagioclase syenites*
(Volume percentages)

	1*	2	3	4	5	6
Analcite	12.0	1.7	21.8	21.4	20.0	8.6
Alkali feldspar	50.9	45.0	30.0	43.8	20.5	52.5
Plagioclase	15.0	30.9	23.4	10.0	26.0	12.0
Kind of plagioclase	An_{52}–An_{44}	An_{55}–An_{38}	An_{44}–An_{44}	An_{38}	.....	An_{34}
Augite	7.4	10.5	9.7	14.2	12.6	8.5
Aegirite-augite	.....	.....	.....	.....	.....	
Olivine	2.4S	4.4S	3.0S	2.5S	3.0	4.1S
Ores	2.6	7.0	3.3	7.6	5.5	3.2
Biotite	0.2	+	3.6	0.5	5.9	2.9
Apatite	0.4	0.5	0.2	+	0.5	0.2
Zeolites	9.1	.....	5.0	+	6.0	8.0
Calcite	.....	.....	.....	+	.....	+

* = Analyzed specimen.
S = Partly or completely replaced by serpentine.

1. Analcite-andesine microsyenite, 1 mile southeast of B. M. 3049.
2. Analcitic andesine microsyenite, half a mile southeast of Mountain 3513.
3. Analcite-andesine microsyenite, 1 mile east of Mountain 4302.
4. Analcite-labradorite syenite, sill west of Sawmill Mountain.
5. Analcite-labradorite syenite, 2 miles southeast of Mountain 3513.
6. Analcite-labradorite microsyensite, 1 mile southwest of Mountain 3518.

but most of the plagioclase is in irregular to quadratic grains with an armor of alkali feldspar. Zoning ranges from An_{52} for the central zones to An_{44}; the average is basic andesine. Augite ($Z \wedge c = 45°$) is grayish violet with a few euhedral crystals. Some grains show a suggestion of greenish aegiritic rims. Anhedral grains of olivine are generally only partly altered to serpentine and rarely are associated with flakes of biotite and grains of iron ore. Iron-ore grains not associated with olivine are sparse. Analcite is mostly clear and colorless. It is an abundant interstitial constituent where it is molded around laths of alkali feldspar and other minerals. It also replaces both plagioclase and orthoclase, though the latter replacement is unusual in these rocks. Apatite is present as minute needles, and there is a trace of calcite. This rock does not show extensive analcitic reaction. Feldspars and olivine are com-

paratively fresh, and the analcite evidently replaced feldspar in the earlier stages of reaction.

Analcite-labradorite syenite.—These rocks show some range in grain size and mineralogy, but the grain size of the freshest specimens approaches the lower limit of the phanerites. A typical example is from a sill flanking Sawmill Mountain on the west. The rock is dark gray, fine-grained with rare minute white specks of zeolites. Its hypidiomorphic granular to subtrachytic texture is controlled by abundant feldspar laths which average about 1 millimeter long. Mineralogically it is much like the syenogabbros except that plagioclase is less abundant, and biotite is not so well developed. In addition to feldspars it contains augite, serpentinized olivine, analcite, iron ores, apatite, and chlorite. Labradorite (An_{58}) is of limited occurrence and has been pretty largely replaced by analcite, albite, and chlorite. It is present mainly as cores of laths armored with alkali feldspar, in some cases the cores being replaced completely by analcite or chlorite. Tabular to irregular slightly larger grains are also present, showing replacement by analcite along cleavage lines and cracks. Rarely these grains show irregular patches of a birefrigent mineral, apparently albite. The alkali feldspar is developed in sharp laths with Carlsbad twinning. These appear to be soda orthoclase since $\gamma = 1.529$ and extinction is parallel on (001) sections, but no determination of the axial angle can be made. Augite ($Z \wedge c = 44°$; $\alpha = 1.706$, $\gamma = 1.729$) is gray with a trace of violet in subhedral crystals. Olivine is completely proxied by brownish-green serpentine, and occasionally these grains form a cluster with biotite and iron ore. Analcite is most abundant as clear limpid interstitial material enclosing augite, alkali feldspar, and iron ore, but it is also present as irregular areas and veinlets replacing feldspar. Certain areas of the interstitial analcite are cloudy or turbid but otherwise do not differ from the rest of the mineral. Traces of calcite are associated with chlorite, replacing feldspar, and in one instance as interstitial material with analcite.

ANALCITE TRACHYANDESITE

Analcite syenodiorite-trachyandesite rocks are rare; those found are aphanitic to very fine-grained and are analcite trachyandesite; all outcrops seen are considerably weathered. Dikes south of B. M. 3313, at the southeast flank of Mountain 4320, west of Yellowjacket Spring, and west of Wildhorse Mountain are classified in this group.

The dike west of Yellowjacket Spring is analcitic trachyandesite. It is dark-gray aphanitic with trachytic texture. Laths of andesine (An_{44}), grains of soda orthoclase, augite, olivine, and iron ore form a matrix

in which are a few microphenocrysts of plagioclase armored with alkali feldspar. There is a very little analcite entirely interstitial. The dikes west of Wildhorse Mountain are mineralogically like the analcitic trachyandesite but coarser and distinctly porphyritic with phenocrysts of andesine (An_{48}) up to 4 millimeters long. Weathering has destroyed most of the mafic minerals in this rock.

The dike at the southeast flank of Mountain 4320 is rich in analcite which has almost completely replaced the plagioclase. The rock is greenish gray, fine-grained to aphanitic with a few andesine phenocrysts 5 millimeters long. The groundmass is rich in orthoclase which is more abundant than plagioclase because of the extensive replacement of the latter by analcite. The extent of reaction in the rock is shown by biotite and aegirite-augite in abundant "reaction nests." Calcite is a weathering product replacing purple augite and other minerals.

ANALCITE SYENOGABBROID ROCKS

Introduction.—Analcite syenogabbro and related rocks are the most abundant analcite-bearing rocks. In addition to those which might be called normal analcite syenogabbro and finer equivalents, there are striking porphyritic rocks and trachydolerites. The available analyses are limited but with the microscopic studies indicate that the porphyries are slightly less basic and the trachydolerites more basic than the syenogabbros.

Analcite syenogabbro.—Analcite syenogabbros and finer-grained equivalents are present in laccoliths, sills, and dikes in the east-central part of the area. They include some of the largest masses of analcite-bearing rocks and some of the coarsest-grained rocks of the whole region. Analcite syenogabbro from the laccolith at Cigar Mountain and Leon Mountain is a coarse-grained "pepper and salt" rock with grains up to 5 millimeters across. Smaller masses, especially thin dikes and sills, contain equivalent rocks in which the grain size makes the rocks microsyenogabbros, and a few are properly classified as analcite trachybasalts.

The most striking rocks of this group are on Cigar Mountain and Leon Mountain. The two mountains probably are the eroded parts of a faulted laccolith whose feeder was at the west flank of Leon Mountain. An isolated small mass immediately northwest of Leon Mountain appears likewise to be a part of the original laccolith. One analyzed specimen (No. XVII, Table 17) is from the top of Cigar Mountain and fairly high in the original continuous uncovered mass. The rock is medium-grained with an average grain size of 2 millimeters with very rare phenocrysts of plagioclase up to 8 by 6 millimeters. It is an even

gray, and examination under a lens shows the rock to be rich in gray feldspar with numerous grains of augite. Under the microscope the rock is a hypidiomorphic granular aggregate of labradorite, purple augite, olivine, iron ores, alkali feldspar, and analcite with small amounts of

TABLE 13.—*Modes of analcite syenogabbro*
(Volume percentages)

	1	2*	3	4	5
Analcite	10.0	24.0	24.4	3.7	16.4
Plagioclase	45.0	33.6	35.3	46.2	43.7
Kind of plagioclase	An_{60}–An_{50}	An_{59}–An_{44}	An_{58}–An_{50}	An_{64}–An_{48}	An_{55}
Orthoclase	16.0	20.0	19.0	27.3	25.0
Augite	8.0A	8.2	9.5A	12.4A	7.0A
Aegirite-augite	.....	.....	.....	.....	+
Olivine	4.0S	4.0	4.5S	4.0S	3.4S
Ores	8.0	7.2	6.0	6.0	4.5
Biotite	4.0	1.0	1.0	+	+
Apatite	1.0	0.2	0.3	+	+
Zeolites	4.0	1.8	.....	.....	.....

* = Analyzed specimen.
A = With aegiritic rims.
S = Serpentinized.

1. South flank of Mountain 4500.
2. Cigar Mountain.
3. Leon Mountain.
4. North of Mountain 3000.
5. Mountain 3000.

biotite, apatite, and alteration products. There is a tendency toward concentration of mafic minerals into clots. Minor constituents are "reaction nests" of minute shreds of biotite, grains of aegirite-augite, and felsitic material. The plagioclase consists of laths and tablets which are zoned and in most cases armored with a narrow rim of alkali feldspar. The inner zones are An_{59}, grading outward to An_{44}. Many of the crystals are partly replaced by analcite and to a lesser extent by zeolites. Augite is grayish-purple titanaugite mainly subhedral with a few smaller euhedral crystals ranging up to 2 by 0.5 millimeter. Twinning is present in some crystals, and basal sections show slight zoning. Olivine is comparatively fresh with only a few crystals showing alteration to serpentine. Some crystals are euhedral 1.2 by 0.8 millimeter, but most are anhedral and smaller. Ores are in scattered anhedral grains from 0.6 millimeter to minute. Analcite replaces plagioclase but is more abundant in interstitial areas where it encloses the earlier-formed minerals. It is generally colorless and has an index of refraction of 1.485. Alkali feldspar (soda

orthoclase, 2V large; extinction = 0° on 001 and 11° on 010) occurs as armor on plagioclase and is discrete untwinned laths. Apatite is present as grains of short prismatic habit 0.3 by 0.07 millimeter. Except in the "reaction nests" biotite is present as minute shreds generally localized near magnetite or olivine grains. The "reaction nests" are discontinuous irregular areas generally not larger than 2 by 3 millimeters. They are composed mainly of finely crystalline faintly birefrigent material in which rare alkali feldspar microlites can be seen. In this general ground are wisps or shreds of reddish-brown biotite, grains of green aegiritic pyroxene, and possibly brown amphibole, though this cannot be distinguished with certainty from the biotite. In some areas zeolites are present. Olivine in contact with these "reaction nests" appears to be more altered than in other areas. The development of these areas in interstitial position and their evident alkalic character suggest that they represent residual magma after the bulk had crystallized to syenogabbro. The border facies of the Cigar Mountain rock is fine-grained approaching aphanitic and is more properly an analcite microsyenogabbro. In it a few plagioclase laths are really phenocrysts, as are rare augites. The rest of the rock is an aggregate of small laths of labradorite and alkali feldspar, prismatic grains of purple augite, and grains of iron ores and altered olivine with abundant clear interstitial analcite. Biotite is very rare, and there are no "reaction nests." The analcite syenogabbro from Leon Mountain includes varieties very similar in hand specimens to those of Cigar Mountain but also some which are decidedly coarser-grained. In the latter, alternating dark and light areas about 6 millimeters in greatest dimension gives a "salt and pepper" aspect to the rock. In the Leon Mountain rocks the mafic minerals are entirely concentrated into clots which are composed of many individual grains of these minerals and minor amounts of feldspars. Laths of alkali feldspar are not so abundant, but the alkali feldspar armor of the labradorite is much more prominent. The plagioclase is labradorite (An_{58}) zoned with basic andesine, but zoning is not prominent. There is a very little green aegiritic pyroxene in small discrete grains, and some augites show narrow greenish rims of the mineral. Biotite is present to a limited extent in the mafic clots. Analcite is abundant as an interstitial material and also replaces labradorite.

A second analyzed specimen (No. XVI, Table 17) is from the lower part of a small sill-like mass 2 miles northeast of Mountain 3518 in which analcite-nepheline syenite also is found. It differs from the rock from Cigar Mountain in having a less calcic plagioclase (An_{52}), turbid analcite, and only a trace of biotite. Olivine is completely serpentinized.

A number of the smaller dikes and sills are composed of aphanitic basaltic rock, the equivalent of analcite syenogabbro. Such a dike is half a mile east of Mountain 3518. The rock is almost microcrystalline with a trachytic texture. Laths of labradorite (An_{54}) and potash feldspar, prismatic grains of gray augite, iron-ore grains, and interstitial analcite are the host for a few crystals of labradorite, augite, iron ore, and olivine which do not exceed 0.2 millimeter.

Analcite trachybasalt porphyry.—Many of the dikes and sills in the northern and east-central part of the area are composed of dark-gray strikingly porphyritic rocks. The groundmass of these rocks is fine-grained to aphanitic and usually encloses numerous lath-shaped or tabular phenocrysts of plagioclase many of which are a centimeter or more long. Through decrease in abundance and size of the phenocrysts the rocks grade into fine-grained or aphanitic rocks of basaltic aspect. Thin section show that these rocks contain analcite and notable amounts of orthoclase along with labradorite and mafic minerals.

The analyzed specimen of analcite trachybasalt porphyry (No. XV, Table 17) is from a dike which does not exceed 3 feet in width but is traceable for over a mile cutting completely across the mass of soda trachyte at Mountain 3513 north of Payne's Waterhole. The rock has a dark-gray fine-grained matrix studded with plagioclase phenocrysts which range from 2 by 2 millimeters to 9 by 13 millimeters. Some of the phenocrysts are platy, but most of them are approximately quadratic. Some of the glittering cleavage faces appear iridescent. The phenocrysts are labradorite with albite twinning and are zoned from cores of An_{64} to outer zones of An_{56}. Some of the phenocrysts are armored with a narrow rim of alkali feldspar, and many likewise have been slightly replaced by analcite along cleavage lines and in branching divergent areas. The groundmass consists of an aggregate of purple augite, plagioclase, alkali feldspar, iron ores, serpentinized olivine, analcite, apatite, and biotite. There is no great difference in size range of these minerals so that a general equigranular appearance results, though the habits are different. The augite is purple titanaugite ($Z \wedge c = 47°$, $\alpha = 1.712$, $\gamma = 1.737$) in subhedral prismatic grains averaging 0.25 by 0.03 millimeter. The plagioclase of the groundmass is labradorite corresponding to the outer zones of the phenocrysts. It is present in laths up to 0.4 millimeter long and in quadratic grains of about the same size. Both laths and quadratic grains show armoring with orthoclase (extinction = 0° on 001, and $\gamma = 1.526$) in Carlsbad-twinned laths averaging 0.25 millimeter long and also as the armor of the plagioclase. Some crystals have altered to chlorite. Original olivine is represented by pseudomorphs

of dark-green serpentine, averaging 0.1 by 0.1 millimeter, with a very few as large as 0.4 by 0.3 millimeter, some of which are euhedral. Iron-ore grains are anhedral, averaging about 0.1 millimeter, with a few also as microphenocrysts up to 0.4 by 0.3 millimeter. Apatite is present as

TABLE 14.—*Modes of analcite trachybasalt porphyry*

(Volume percentages)

	1	2	3*	4
Analcite	8.6	4.0	3.8	3.6
Orthoclase	23.0	22.0	33.0	34.0
Plagioclase	46.8	47.3	34.7	35.4
Kind of plagioclase	An_{58}	An_{54}	An_{64}–An_{56}	An_{54}
Augite	8.8	13.9	11.7A	18.9
Olivine	2.8S	3.4S	9.0S	2.5
Ores	10.0	9.4	7.8	5.6
Biotite	+	+	+	.....
Apatite	+	+	+	.....
Zeolites	+	.....	+	+
Calcite	+	.....	.....	+

* = Analyzed specimen.
A = With aegiritic rims.
S = Serpentinized.

1. Analcite trachybasalt porphyry dike, cutting rhyolite, 1½ miles southwest of Mountain 4320.
2. Analcitic trachybasalt porphyry sill, one-half mile east of Packsaddle Mountain.
3. Analcitic trachybasalt porphyry, Mountain 3513.
4. Analcitic trachybasalt porphyry, 1 mile east of Payne's Waterhole.

minute needles. Rare biotite flakes are associated with serpentine and ores. Some analcite is clear and some turbid. It is developed as wedge-shaped interstitial grains and also replaces plagioclase. Rare small amygdules are filled with the mineral in association with zeolites and calcite. A few "reaction nests" 2 millimeters in diameter are present.

The analyzed specimen is fairly representative of the type, though it contains somewhat more alkali feldspar and less analcite than some representatives. It occupies a medium position with respect to grain size of the groundmass. Minor mineralogical variation exists among the various examples of the type, though some of this may be more apparent than real. The rock from a small pluglike mass west of Adobe Walls contains reddish-brown bowlingsite instead of green serpentine as the alteration product of olivine. The rock of a sill east of Packsaddle Mountain contains unaltered olivine, and a number of examples contain

fat prisms of apatite rather than the slender needles of the analyzed specimen. Sections from a dike just east of Mountain 3513 show a number of the "reaction nests" with the usual wispy biotite, aegirite, and felsitic paste, and this feature is generally present to a limited extent in most examples.

A dike a mile east of Payne's Waterhole exhibits a decided quenched effect. The phenocrysts reach a maximum size of 7 by 4 millimeters, but most of them are slender laths about 5 millimeters long. There are microphenocrysts of olivine only slightly altered up to 0.6 by 0.4 millimeter and of iron-ore grains to 0.4 millimeter. This groundmass is dominated by purple augite microlites averaging 0.25 millimeter long and arranged in parallel or subparallel bundles. Many of the rods of the augite are studded with minute iron-ore grains. Space between rods or groups of microlites is occupied by alkali feldspar and rarely by analcite. Analcite is limited in amount and replaces plagioclase to only a slight extent. The rock represents a minimum of reaction, and practically all the analcite can be regarded as late magmatic.

A number of the analcite trachybasalt porphyries show decidedly chilled border selvages. These are basaltic without phenocrysts or with phenocrysts much smaller than those of the central part of the mass. There are no pronounced mineralogical differences, but there is a tendency toward trachytic texture and less evidence of analcitic reaction. In some specimens analcite is very scarce. The plagioclase phenocrysts or microphenocrysts are slightly more basic than those of the center of the mass.

Analcite trachydolerite.—The analcite trachydolerites form a distinctive group of rocks. The largest masses which are sills are southwest of Agua Fria Mountain, but dikes are found as far southeast as Wildhorse Mountain. There are dikes and sills north of Payne's Waterhole and two small laccoliths and several sills in the area east of Yellow Hill and north of Saltgrass Draw.

The rocks are mostly fine-grained, medium to dark gray, and relatively fresh. Specimens from some of the thinner dikes and sills are aphanitic, and in one occurrence, that near Wildhorse Mountain, the rock has been so quickly chilled that it can be called a quenched rock. Specimens from the center of the laccolith near Yellow Hill are medium- to coarse-grained. A sill only 5 feet thick southwest of Agua Fria Mountain contains remarkable porphyritic analcite trachydolerite with plagioclase crystals up to 5 inches long; many several inches long are in a fine-grained matrix. Many of the dikes and sills show chilled selvages some of which contain considerable amounts of zeolites.

Mineralogically these rocks are comparatively simple assemblages of plagioclase, which generally is medium labradorite with zoning into sodic labradorite or andesine, purple augite, olivine generally with only limited serpentinization, iron ores, alkali feldspar (orthoclase, sanidine), small

TABLE 15.—*Modes of analcite trachydolerite*
(Volume percentages)

	1	2	3*	4	5	6	7
Analcite	5.9	7.1	11.8	6.0	11.7	2.7	0.5
Alkali feldspar	10.6	10.7	15.0	20.0	8.0	13.0	9.0
Plagioclase	55.8	56.4	46.1	47.7	49.1	60.7	53.8
Kind of plagioclase	An_{50}	An_{50}	An_{50}	An_{56}	An_{62}–An_{48}	An_{58}–An_{40}	An_{60}
Augite	11.7	12.6	11.8	12.8	13.7	8.4	13.0
Olivine	7.4	7.9	7.2	6.9S	6.8	8.8S	16.3S
Ores	8.4	5.0	8.1	6.4	10.4	6.2	7.3
Biotite	0.1	+	+	.....	0.2	0.1	.....
Apatite	0.1	0.3	+	0.2	0.1	0.1	.....
Zeolite	+	.....	+	.....	.....	.....	0.1

* = Analyzed specimen.
S = Serpentinized.

1. 2 miles northeast of Pink's Peak.
2. 2½ miles east of Yellow Hill.
3. 1 mile northeast of Mountain 3513.
4. South flank of Agua Fria Mountain.
5. 1 mile southeast of Mountain 3415.
6. 2½ miles east of Yellow Hill.
7. South flank of Wildhorse Mountain.

to moderate amounts of interstitial analcite, traces of biotite and apatite, and sometimes zeolites. The extensive reaction so common in some of the other analcite rocks is not found in the analcite trachydolerites. In some there is a very slight development of aegiritic rims on augite and considerable replacement of plagioclase but not to the extent common in the other rocks. Augite is titanaugite and in some specimens has an intense purple color approaching red. Alkali feldspar is less abundant than in the analcite syenogabbros and analcite trachybasalt porphyries.

The analyzed specimen (No. XIX, Table 17), which is representative, is from a sill 200 feet thick 1 mile northeast of Mountain 3513, located in a structurally low area between two small anticlines. The resulting outcrop is a V-shaped mass, the north leg of which is on the flank of one anticline while the south leg is on the flank of the other anticline. The sill has formed a barrier to an intermittent stream which has cut a narrow

gap through the igneous rock, resulting in one of the common potholes of the region. Here the sill dips 45° S. and is inclosed in the Late Upper Cretaceous beds. Two sets of joints at right angles follow the course of the sill, and small stringers 2 inches thick of lighter analcitic syenite cut the trachydolerite. The rock is medium gray, fine-grained, with markedly ophitic texture in which feldspar elements are trachytic. Light-purple augite ($Z \wedge c = 53°$) is present in spongelike crystals up to 2 millimeters in greatest dimensions. In places these are almost poikilitic to feldspar but commonly are ophitic. The feldspar includes labradorite (An_{59}) in sharp laths with albite twinning up to 0.8 millimeter long and orthoclase in smaller laths and irregular interstitial grains. Anhedral olivine grains up to 0.3 millimeter are partly serpentinized and associated with euhedral grains of iron ore 0.2 millimeter across. Apatite is present in fat euhedral prisms. Analcite is clear and colorless and mainly is interstitial, only slightly replacing plagioclase.

ANALCITE GABBROID ROCKS

Gabbroid analcite rocks are rare in the region. Only a few examples have been found in which the amount of potash feldspar is sufficiently small to justify calling the rocks gabbros. Most of the rocks are simply analcite syenogabbro, analcite trachydolerite, or analcite trachybasalt in which potash feldspar is relatively scarce. One or two are definitely more melanocratic.

A sill 25 feet thick outcropping along the lower eastern flank of Mountain 3429 in the east part of the area is analcite gabbro. The rock is gray, medium-grained, with a few feldspar phenocrysts up to 3 millimeters. Biotite flakes and augite grains are visible in the hand specimen. Under the microscope the rock consists of laths of labradorite (An_{60}) averaging 1 millimeter long armored with potash feldspar in a hypidiomorphic granular groundmass of feldspar, purplish-gray augite, iron ore, serpentinized olivine, and analcite with a range from 0.07 to 0.4 millimeter. Some of the augite has narrow aegiritic rims. The smaller feldspar is soda orthoclase (extinction = 0° on 001 and 8° on 010) in clear laths, a few of which are Carlsbad twins. Analcite replaces plagioclase but is largely interstitial where it is turbid and in some grains slightly birefringent. Needles and prisms of apatite are a minor accessory.

A few of the analcite rocks with ophitic texture contain only a small amount of potash feldspar and are analcitic diabasic microgabbro. Most of these rocks are in the area south of Agua Fria Mountain, Black Ridge being the most noteworthy example. The rock is dark gray, medium-grained ophitic, roughly equigranular with a seriate relation between the grains of specific minerals. Plagioclase up to 2 millimeters is labradorite

zoned from An_{60} to An_{52} and armored with potash feldspar. Augite is grayish violet up to 1 millimeter and is ophitic to plagioclase, and olivine only slightly serpentinized is the same size as augite. Iron-ore grains average 0.2 millimeter. A very small amount of biotite is present as

TABLE 16.—*Modes of analcite gabbroid rocks*

(Volume percentages)

	1	2	3	4	5*
Analcite	14.1	2.7	2.6	1.5	10.9
Alkali feldspar	65.5	69.7	6.0	72.7	20.6
Plagioclase			56.1		
Kind of plagioclase	An_{60}	An_{60}–An_{55}	An_{63}	An_{56}	An_{62}
Augite	7.0A	13.7	12.3	10.7	47.0
Olivine	4.9	5.9	10.2	9.2	13.9S
Ores	6.8	7.7	12.8	5.4	7.6
Biotite	1.7	0.2	+	.....	+
Hornblende	.....	.....	.....	0.5	+
Apatite	+	0.1	+	+	+
Zeolites	.....	+	.....	.....	.....

* = Analyzed specimen.
A = Aegiritic rims.
S = Replaced by serpentine and carbonate.

1. Analcite gabbro, east flank of Mountain 3429.
2. Analcitic diabasic microgabbro, Black Ridge.
3. Analcitic diabasic microgabbro, west flank of Agua Fria Mountain.
4. Analcitic basalt, Clay Mountain.
5. Analcitic picritic basalt southeast of Mountain 4500.

reaction rims with iron-ore grains on olivine and augite. Clear colorless analcite replaces plagioclase and also is interstitial. There are rare smaller tablets of soda orthoclase (?), but most of the potash feldspar is present as rims on the plagioclase.

The igneous rock of Clay Mountain west of Terlingua is an analcitic basalt. The rock occurs in an irregularly elongate oval mass about 200 yards long and 100 yards wide intruded into Lower Cretaceous sediments, which here are at the surface. The igneous mass probably represents a vent or feeder channel because purplish-gray volcanic breccia and limestone inclusions occur in the basalt.

The rock is dense black with occasional grains of olivine and in certain areas rare phenocrysts of black augite as much as 1 centimeter long. Under the microscope the rock is seen to be a beautifully fresh labradorite-

rich analcitic basalt with seriate range in grain size of all constituents. Laths of plagioclase (An_{56}) range from minute to 1.4 by 0.2 millimeter. Some of these show a very narrow rim of alkali feldspar armor. There is a very slight replacement by analcite, and minute inclusions of augite are not uncommon. The augite ($Z \wedge c = 47°$, $\alpha = 1.712$, $\gamma = 1.737$) is gray and is present in subhedral crystals from minute to 0.4 by 0.3 millimeter. Olivine ($\alpha = 1.660$, $\gamma = 1.695$) is fresh and colorless in subhedral crystals up to 0.5 by 0.4 millimeter. Iron-ore grains are minute anhedral. Analcite is almost entirely interstitial and is clear and colorless. Minute apatite needles are common, and scattered through the rock are minute flakes of a purplish isotropic substance of low index of refraction.

A small pluglike mass of basaltic rock 1 mile southeast of Mountain 4500 (No. XXI, Table 17) is analcitic picritic basalt, the most highly melanocratic analcite-bearing rock of the region. The mass is oval, about 200 yards in greatest dimension, and appears to cut vertically through the Upper Cretaceous sediments. It is somewhat weathered but is obviously a heavy basic variety, very fine-grained with a few visible cleavages of mafic minerals. The rock is microporphyritic with microphenocrysts of augite, altered olivine, and labradorite in a groundmass of augite, iron ores, and minor amounts of biotite, hornblende, analcite, and possibly alkali feldspar. The augite microphenocrysts are gray, frequently zoned, and reach 0.7 by 0.4 millimeter. The olivine is the most prominent phenocryst material but is entirely replaced by serpentine and calcite. Many of the pseudomorphs show euhedral outlines and reach 1.25 millimeters. The calcite replaces the serpentine either partially or completely, thus accounting for the excessive amount of carbon dioxide in the analysis of the rock. The plagioclase is labradorite (An_{62}) and is present in rare anhedral grains with numerous inclusions of augite, altered olivine, and ores. It is the host for much of the groundmass material so that a subpoikilitic texture results. The groundmass augite is similar to that of the phenocrysts and is present as subhedral to euhedral crystals averaging 0.1 by 0.02 millimeter. The iron-ore grains are not abundant and occupy a size range between that of the microphenocrysts and the groundmass minerals. They are euhedral, averaging 0.15 by 0.15 millimeter. Reddish-brown biotite flakes and subhedral crystals of brownish-red hornblende ($Z \wedge c = 15°$) of the same size range as augite are scattered sparingly through the sections. Analcite is interstitial and is both clear and turbid, both types being present in the same grain. Some areas of the mineral show outlines suggesting crystal boundaries. The mineral has not replaced plagioclase or other minerals. Alkali feldspar has not been identified in the rock, but limited areas of chloritic

	I	II	
SiO_2	76.71	76.23	7
Al_2O_3	12.15	12.11	1
Fe_2O_3	0.94	0.42	
FeO	0.60		
MgO	0.18	0.46	
CaO	0.05	0.36	
Na_2O	4.73	1.40	
K_2O	3.88	4.93	
H_2O+	0.31	1.47	
H_2O-	0.11	1.80	
CO_2	.....	.....	
TiO_2	0.09	0.13	
P_2O_5	0.02	0.01	
MnO	.....	.....	
SO_3	.....	.....	
Ign. Loss	.....	0.92	
	99.77	100.24	9

Q	34.68	47.94	3
or	22.80	28.91	2
ab	39.82	12.05	4
an	0.28	1.39	
ne	.....	.....	
C	.....	3.98	
di	.....	.....	
hy	0.66	1.13	
acm	.....	.....	
ol	.....	.....	
wo	.....	.....	
mt	1.16	0.23	
hm	.....	.....	
il	0.15	0.15	
ap	.....	.....	
ru	.....	.....	
pf	.....	.....	
calcite	.....	.....	

* = Locations from whic

I. Paisanitic riebeck

II. Potassic rhyolite,

III. Paisanitic riebeck

IV. Sodipotassic rhyo

V. Paisanitic riebeck

VI. Biotite-augite gr

VII. Trachyte, three-f

VIII. Soda trachyte, M

IX. Weathered soda

X. Soda trachyte fr

TABLE 17.—*Analyses of rocks of Terlingua-Solitario region, Texas**

(R. B. Ellestad, analyst)

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX	X
76.71	76.23	75.53	74.72	74.35	68.13	64.75	63.42	62.87	60.35	59.62	59.31	55.48	52.98	49.80	47.31	46.87	46.00	44.81	43.65	4
12.15	12.11	12.26	14.12	12.82	16.00	15.29	16.02	14.55	16.12	17.89	17.94	17.57	18.01	18.38	16.95	17.04	15.93	16.81	13.16	1
0.94	} 0.42	1.56	} 0.38	1.37	1.92	5.41	3.23	5.89	2.00	3.97	2.33	2.06	2.26	1.84	4.88	3.12	1.85	4.06	3.35	
0.60		0.73		0.82	1.12	0.22	2.69	0.08	1.87	1.83	1.95	4.89	5.54	7.57	4.41	6.81	7.61	7.19	7.00	
0.18	0.46	0.07	0.19	0.16	0.51	0.11	0.16	0.20	0.23	0.75	1.53	2.41	1.85	2.63	2.92	3.35	8.91	4.21	12.48	1
0.05	0.36	0.16	0.26	0.14	1.31	0.39	1.63	2.68	4.15	2.78	3.58	3.84	4.35	7.09	6.10	7.66	9.28	7.21	12.18	1
4.73	1.40	5.24	3.77	5.19	5.46	5.13	6.12	4.63	6.87	6.20	6.06	5.68	6.44	4.94	5.78	5.13	4.11	4.65	2.43	
3.88	4.93	4.05	4.57	4.36	4.73	5.25	5.30	5.25	5.02	4.55	4.15	3.96	3.89	2.60	3.01	2.39	1.85	1.97	1.30	
0.31	1.47	0.00	0.95	0.17	0.18	1.20	0.34	1.01	0.24	0.71	0.45	0.89	2.45	1.73	4.44	2.99	1.38	3.70	1.79	
0.11	1.80	0.13	0.33	0.06	0.24	0.33	0.48	0.08	0.15	0.38	0.41	0.33	0.24	0.27	0.62	0.21	0.12	1.07	0.19	
.....	.....	.....	.....	.....	.....	.....	.....	1.85	2.86	.....	0.75	.....	.....	.....	0.42	.....	.....	.....	0.10	
0.09	0.13	0.10	0.12	0.14	0.30	0.35	0.36	0.54	0.15	0.66	1.11	1.57	1.64	2.30	2.33	2.96	2.26	3.27	1.55	
0.02	0.01	0.01	0.02	0.02	0.12	0.05	0.06	0.11	0.02	0.26	0.48	0.95	0.54	0.95	0.83	0.93	0.62	1.04	0.63	
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.19	.....	.....	.....	
.....	.....	.....	.....	.....	.....	1.47	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	
.....	0.92	.....	0.56	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	
99.77	100.24	99.84	99.99	99.60	100.02	99.95	99.81	99.74	100.03	99.60	100.05	99.63	100.19	100.10	100.00	99.65	99.92	99.99	99.81	9

Norms

4.68	47.94	30.06	34.50	27.48	15.66	14.70	5.16	15.18	0.38	1.02	2.16	.....	.....	.....	.....	.....	.....	.....	.....	
2.80	28.91	23.91	27.24	25.58	27.80	30.58	31.14	31.14	30.02	26.69	24.46	23.35	22.80	15.57	17.79	14.46	10.56	11.68	7.78	
9.82	12.05	40.35	31.44	41.39	45.59	42.97	51.35	38.77	54.49	52.40	50.83	45.59	35.46	31.44	28.82	25.68	14.41	26.76	4.98	1
0.28	1.39	.....	1.11	.....	5.56	1.39	0.83	0.56	.....	7.51	9.45	10.84	8.90	20.29	11.68	16.40	19.74	19.18	21.13	2
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	1.14	9.94	5.40	10.56	9.37	10.93	6.82	8.37	
.....	3.98	.....	2.55	.....	.....	0.82	.....	2.04	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	
.....	.....	0.46	.....	.....	.....	.....	4.31	0.50	0.71	3.46	.....	2.29	8.10	7.64	10.21	13.14	18.54	8.07	28.06	
0.66	1.13	0.66	0.40	1.19	1.20	0.20	.....	.....	2.64	0.40	3.80	.....	.....	.....	.....	.....	.....	.....	.....	
.....	.....	.....	.....	2.31	.....	.....	.....	.....	2.77	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	7.04	5.53	8.43	1.96	5.11	16.06	9.11	18.11	1
.....	.....	.....	.....	.....	.....	.....	0.58	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	
1.16	0.23	0.70	0.41	0.93	2.78	.....	4.64	.....	1.62	3.94	3.02	3.02	3.25	2.55	6.96	4.41	2.55	5.80	4.87	
.....	.....	.....	.....	.....	.....	5.44	.....	5.76	.....	1.28	0.16	.....	.....	.....	.....	.....	.....	.....	.....	
0.15	0.15	0.15	0.15	0.15	0.46	0.46	0.76	0.15	0.15	1.22	2.13	2.89	2.89	4.41	4.41	5.62	4.10	6.08	2.89	
.....	.....	.....	.....	0.34	1.01	0.17	0.34	.....	0.67	0.67	1.34	2.02	1.01	2.02	2.02	2.02	1.34	2.35	1.34	
.....	.....	.....	.....	.....	.....	0.08	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	
.....	.....	.....	.....	.....	.....	.....	.....	0.58	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	
.....	.....	.....	.....	.....	.....	.....	.....	4.10	6.50	.....	1.60	.....	.....	.....	.....	.....	.....	.....	0.20	1

ons from which samples were collected are shown on Plates 1 and 2.

isanitic riebeckite soda rhyolite, east of Mountain 4500.

tassic rhyolite, East Tank, Solitario.

isanitic riebeckite soda rhyolite, Mountain 4500.

dipotassic rhyolite, southwest part of Solitario.

isanitic riebeckite soda rhyolite, Mountain 4638.

otite-augite granophyre, main mass of Wildhorse Mountain.

achyte, three-fourths mile south of B. M. 3049.

da trachyte, Mountain 3513 northwest of Payne's Waterhole.

eathered soda rhyolite north of Mud Spring.

da trachyte from sill-like mass 1 mile southwest of Mountain 4320.

XI. Analcitic microsyenite, Sawmill Mountain.

XII. Syenodiorite porphyry, southeast flank vent area, Solitario.

XIII. Analcitic microsyenite, Solitario.

XIV. Analcite-plagioclase syenite, 1 mile southeast of B. M. 3049.

XV. Analcite trachybasalt porphyry, Mountain 3513.

XVI. Analcite syenogabbro, 2 miles northeast of Mountain 3518.

XVII. Analcite syenogabbro, Cigar Mountain.

XVIII. Lamprophyric basalt, near B. M. 2671 on Alpine road.

XIX. Analcite trachydolerite, 1 mile northeast of Mountain 3513.

XX. Picritic basalt, Mountain 3607.

XXI. Analcite picritic basalt, 1½ miles southeast of Mountain 450

material like that in other analcite-bearing rocks suggest the presence of the mineral.

PETROLOGY

Chemical analyses of the Terlingua-Solitario rocks are brought together in Table 17, and although these are limited in number and do not include

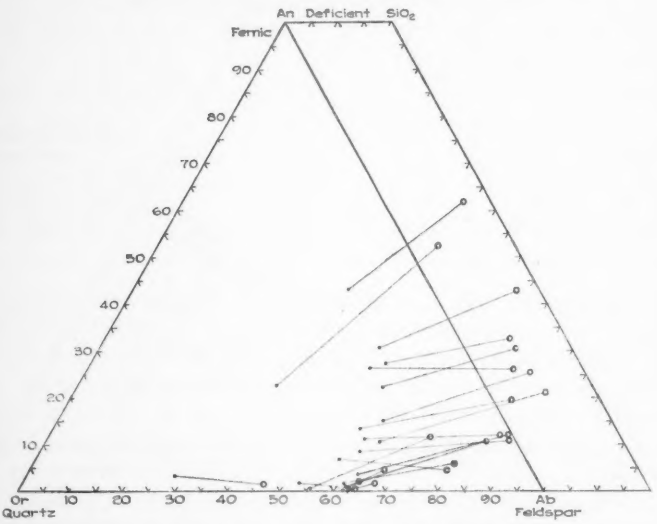

FIGURE 4.—*Variation diagram for rocks of Terlingua-Solitario region*
Dots are or-ab-an; circles are normative quartz (or deficient SiO_2)-feldspar-femic.

all rock types it is evident that they represent an alkaline rock group slightly dominant in soda with potash persisting in notable amounts in even the most basic varieties. The region is another of the alkaline subprovinces at the front of the Rocky Mountains, thus extended still farther southward.

Triangular variation diagrams according to Larsen (1938) of the Texas rocks and of those of several of the other alkaline provinces are shown in Figures 4 to 8. In these diagrams the direction of slope and length of the lines produce a pattern characteristic of the rocks concerned. The Highwood Mountains rocks yield long lines sloping steeply downward to the left with only a few erratic lines. The Texas and Spanish Peaks rocks yield lines most of which slope downward to the left but also yield several lines sloping downward to the right. The diagram from the Little Belt Mountains is much the same as those of the Ter-

lingua-Solitario and Spanish Peaks areas with, however, a greater proportion of lines sloping downward to the right. In the diagram from the Crazy Mountains the two kinds of lines are about equal in number, and the resulting pattern appears more like those of some of the lime-

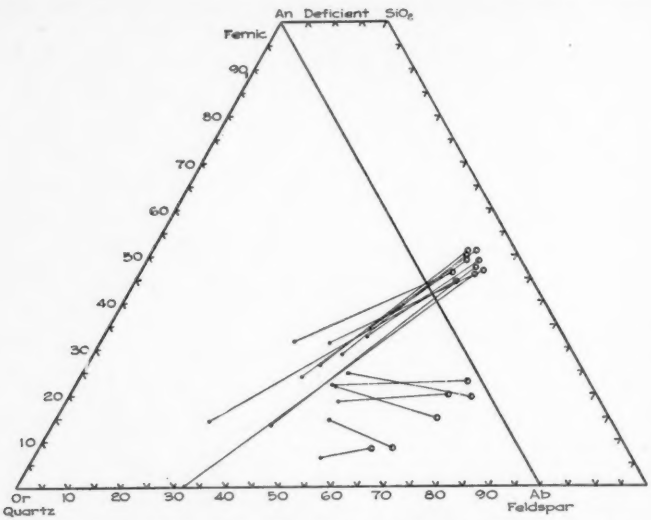

FIGURE 5.—*Variation diagram for rocks of Spanish Peaks, Colorado*
Dots are or-ab-an; circles are normative quartz (or deficient SiO_2)-feldspar-femic.

alkali provinces shown by Larsen (1938, p. 518-519) in which the greater number of lines slope downward to the right. The Terlingua-Solitario diagram is most nearly like those of Spanish Peaks and Little Belt Mountains. In all the diagrams, the feldspar ends of the lines show a certain degree of grouping or crowding in an intermediate area with respect to the total range of the feldspars. The range of the normative feldspars in the crowded area reflects the general chemical character of the province provided the sampling has been fairly representative.

All the rock groups compared in Table 18 show dominance of the alkali normative feldspars, with the Highwood Mountains more strongly potassic than the others. The Terlingua-Solitario rocks are comparatively rich in normative albite but also contain notable amounts of normative orthoclase and a rather wide range in normative anorthite. Similar diagrams by Larsen of a number of lime-alkali provinces show anorthite more important in the characteristic range, and albite and orthoclase with approximately the same range.

The general petrology of the Terlingua-Solitario rocks is a problem of many hypabyssal masses of diverse but related character. The analcite-bearing rocks are of unusual interest. In most of the described localities, the dominant types are gabbros or diabases with generally a facies called syenite in which orthoclase predominates over plagioclase.

TABLE 18.—*Characteristic normative feldspar range*

	Ab	Or	An
Terlingua-Solitario	41–63	16–31	3–31
Spanish Peaks	37–52	24–34	15–27
Little Belt Mountains	46–53	30–41	8–21
Highwood Mountains	20–43	45–60	2–22
Crazy Mountains	56–62	23–34	8–27

The greatest development of these rocks is in Scottish localities, and there olivine-bearing types with little or no orthoclase have been called crinanite and types with small to notable amounts of orthoclase teschenite. In the United States, generally similar rocks have been called analcite diabase. In the Terlingua-Solitario suite the most abundant type has been called analcite syenogabbro (or mineralogical equivalents) and contains labradorite, potash feldspar, purple augite, olivine, and analcite. It generally is richer in orthoclase, labradorite, and analcite and poorer in mafic minerals than the Scottish teschenites or American analcite diabases. The Texas rocks include a very few examples of types approaching the more melanocratic of the Scottish teschenites and the analcite diabase of Gilluly (1927). Examples lacking orthoclase or matrix equivalent and closely resembling crinanite have not been found. The syenite facies includes examples very close to the Scottish analcime syenite from Howford Bridge (Tyrrell, 1928, p. 558) and not greatly different from the analcite syenites from Utah and Colorado, though lacking hornblende which is present in the latter. A few examples, however, contain less calcic plagioclase and approach an analcite syenite from Pleasant Mountain, Maine (Jenks, 1934). In addition to these end and intermediate types the Texas rocks include others of intermediate character so that a fairly complete gradation exists constituting probably the most complete series of the kind yet found.

The analcite-bearing rocks obviously are a related series and originated through differentiation which proceeded from melanocratic types through labradorite-rich types to syenitic facies. The amount and kind of reac-

tion shown in the rocks parallel the place of the rocks in the series, and contact relations show that syenitic types are youngest. In only a few instances is more than one variety of analcite-bearing rock found in the same mass. Some of the dikes show basic selvages, and analcite syenite

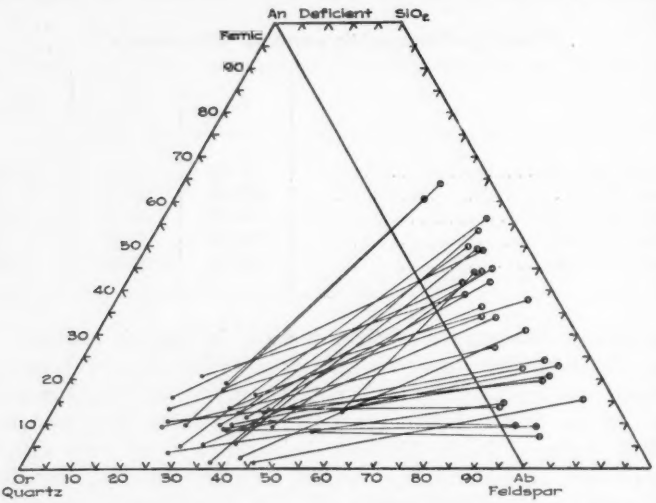

FIGURE 6.—*Variation diagram for rocks of Highwood Mountains, Montana*
Dots are or-ab-an; circles are normative quartz (or deficient SiO_2)-feldspar-femic. (From Larsen, 1938, p. 519.)

stringers are found in a dike of analcite trachydolerite, but most of the rock masses are composed of one type of rock. The great number of types of the rocks demands a differentiating magma fractionated periodically during the course of differentiation or several differentiating magmas of different original composition.

Gilluly (1927, p. 208) in explaining the Utah analcite rocks pictures a diabasic source magma in a somewhat advanced stage of differentiation. Differentiates from this might be a picritic rock and a syenitic one. Only the syenitic phase was exposed, intruding the diabase. In the Terlingua-Solitario region fractions generally similar to those described by Gilluly are exposed in dikes and plugs of analcite-bearing picritic or lamprophyric basalts, dikes and sills of trachydolerite, and various masses of syenitic types. A process much like that described by Gilluly, with one differentiating magma, could account for a limited number of varieties, such as these, but probably could not be extended to include all the

varieties, because this would call for a nearly perfect mechanism of fractionation.

The origin of these rocks very likely is connected with the tectonic history of the area. The key seems to be in the sunken block and its

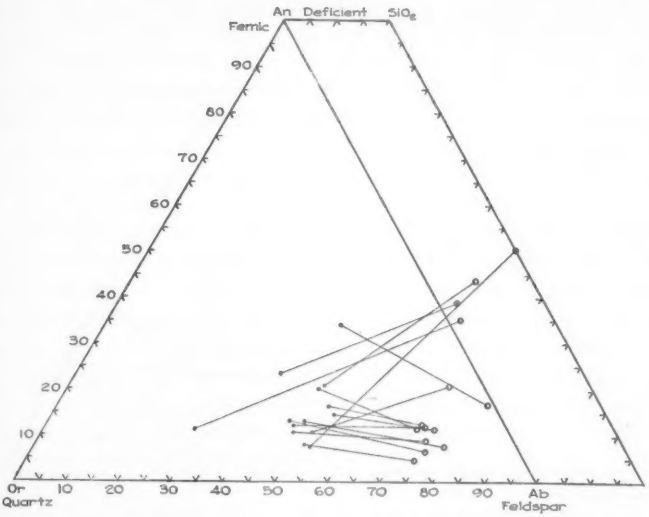

FIGURE 7.—*Variation diagram for rocks of Little Belt Mountains, Montana*
Dots are or-ab-an; circles are normative quartz (or deficient SiO_2)-feldspar-femic.

numerous laccoliths and other minor intrusions. Baker (1935, p. 537), in discussing the quicksilver deposits, has suggested that the Solitario uplift is underlain by a batholith with a steep downward slope on the south flank. In the sunken block in which nearly all the analcite-bearing rocks are found, it is possible that the sinking of the area resulted in the rise of magma drawn from a lower and relatively basic part of the batholith. The result would be not a single immediate source for all the analcite-bearing rocks (as in Utah) but a number of differentiating masses in the laccoliths and other minor intrusions from which, in the total, a relatively large number of varieties might be produced. A slight difference in composition of the magmas in the laccoliths and other bodies above the roof of the batholith would account for the various types of analcite-bearing rocks. Gabbroid magma could produce picritic and syenitic types, as postulated by Gilluly, and dioritic or syenodioritic

magma could account for the other intermediate types which are difficult to visualize as the products of one magma. There is no proof that the rocks originated in this manner, but the great number of small hypabyssal masses, their relatively wide distribution and variety, and their location

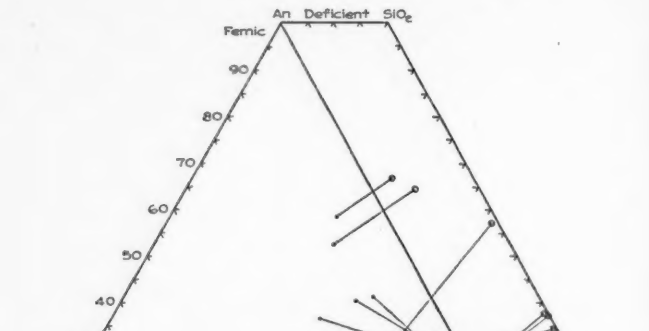

FIGURE 8.—*Variation diagram for rocks of Crazy Mountains, Montana*
Dots are or-ab-an; circles are normative quartz (or deficient SiO_2)-feldspar-femic.

with respect to the sunken block appear to make this a plausible explanation.

The analcite-bearing rocks constitute only about half of the igneous rocks. The others include a very few basalts, probably directly related to the analcite-bearing rocks, many bodies of syenodioritic rocks, sodic and nonsodic trachytes, and sodic and nonsodic rhyolites. The latter appear to be related because they generally are alkaline, and many of them contain special minerals such as anorthoclase which indicate kinship. Their relation to the analcite-bearing rocks is not so evident, but unless they resulted from igneous activity of a distinctly different age (which has not been detected) the field associations indicate that both groups had their ultimate origin in the same regional magma. In addition, a few analcitic syenitic rocks are not greatly different from some of the soda microsyenites. Many of these rocks antedate the analcite-bearing rocks, though some types were intruded in two periods, before

and after the analcite rocks, and some were formed (partly at least) after some of the analcitic rocks started to crystallize. The great abundance of rhyolite associated with syenodiorite in the Solitario and of rhyolite in other higher structures suggests that the Solitario and other high structures were centers of early differentiation above the upper part of the regional batholith, with original differences in composition which produced fractions different from those resulting from differentiating magmas in the sunken block. Members of the two groups are not entirely restricted to the contrasted structural areas for there is one mass of analcitic rock in the Solitario and numerous masses of trachytic and rhyolitic rocks in the sunken block. Furthermore, there are types such as some of the syenodiorites, soda trachytes, and soda rhyolites whose affinity to one group or the other is not certain. There is, however, a distinct difference in general distribution of the two groups. It is postulated that, in a period early in the emplacement of a regional batholith of intermediate composition, differentiation produced varieties ranging through syenodiorite, soda trachyte, soda rhyolite, to rhyolite. These are concentrated mainly in and around larger laccoliths above the batholith, but there are minor masses throughout the entire area. Sinking of the eastern area and development of the analcitic rocks started before differentiation of the other series was completed so that the two groups overlap in age and to some extent in areal distribution.

This principle of tectonic control of differentiation probably operated beyond the area considered here. The Chisos Mountains uplift east of the area, though larger, is comparable to the Solitario in magnitude and position. Its rocks are alkaline and include types found in the Terlingua-Solitario region. A fairly complete collection of the rocks contains only a few analcite-bearing specimens, and these are from localities well down on the flanks of the uplift or actually in the sunken block.

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